1991

Influence of root system morphology and site characteristics on development of transplanted northern red oak (Quercus rubra L.) seedlings

Janette R. Thompson
Iowa State University

Order Number 9212199

Influence of root system morphology and site characteristics on development of transplanted northern red oak (*Quercus rubra* L.) seedlings

Thompson, Janette Ridley, Ph.D.

Iowa State University, 1991

U·M·I
300 N. Zeeb Rd.
Ann Arbor, MI 48106

Influence of root system morphology and site characteristics on development of transplanted northern red oak (*Quercus rubra* L.) seedlings

by

Janette R. Thompson

A Dissertation Submitted to the
Graduate Faculty in Partial Fulfillment of the
Requirements for the Degree of
DOCTOR OF PHILOSOPHY

Department: Forestry
Major: Forestry (Forest Biology-Wood Science)

Approved:

Signature was redacted for privacy.

In Charge of Major Work

Signature was redacted for privacy.

For the Major Department

Signature was redacted for privacy.

For the Graduate College

Iowa State University
Ames, Iowa

1991

TABLE OF CONTENTS

GENERAL INTRODUCTION

Northern red oak (*Quercus rubra* L.) is a widely distributed and commercially important tree in the eastern half of the United States (Fowells, 1965; Lyford, 1980). The natural range of red oak extends from the east coast of North America westward to extreme eastern Nebraska, Oklahoma, and Kansas, and from southern Louisiana northward to southern Ontario, Quebec, and New Brunswick, Canada (Fowells, 1965).

Northern red oak is one of the most highly prized hardwood species in North America for lumber and veneer products (Spencer and Kingsley, 1991). In addition to its high value for timber, red oak is also a valuable species for wildlife habitat and aesthetic purposes.

Spencer and Kingsley (1991) estimated that seedling-sapling stands represent only 17 % of the oak forest area in the upper midwest (Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, and Wisconsin), compared with poletimber (29 % of oak area) and sawtimber (54 % of oak area) stands. The small proportion of oaks in seedling-sapling stands reflects the general inadequacy of natural regeneration for the oaks, which without intervention often leads to succession of oak-type forests to more tolerant and less desireable species (Dickson, 1991; Spencer and Kingsley, 1991). In recent years more attention has been given to artificial regeneration of red oak, due to the failure of natural regeneration of this species in silviculturally harvested stands (Dixon et al., 1984; Dickson and Tomlinson, 1989).

In fact, obtaining adequate stands of northern red oak has been difficult with either natural or artificial regeneration techniques (Teclaw and Isebrands, 1991). This may be primarily related to the conservative shoot growth characteristic of the species: under stressful conditions, any photosynthate produced in excess of seedling respiratory requirements is allocated to root growth or storage at the expense of top growth (Johnson, 1988; Dickson, 1991; Teclaw and Isebrands, 1991). Slow shoot growth is a distinct disadvantage on relatively good sites where animal damage and intense competition from weeds may cause seedlings to be overtopped and suppressed (Dixon et al., 1984).

Because of local concerns about erosion control and agricultural diversification, as well as economic incentives (e.g. federal set-aside programs, particularly the Conservation Reserve Program instituted in 1986), many previously forested areas of the midwest that had been cleared for rowcrop agriculture are now being returned to native vegetation through artificial regeneration (McCormick and Bowersox, 1989; Schultz and Thompson, 1991). Consequently, the demand for seedlings of the quality hardwood species, including red oak, has increased tremendously throughout the midwest over the past few years (Overton, 1989). The majority of reforestation projects have utilized planting stock grown in conventional nurseries and shipped as one- or two-year-old bare-root seedlings. However, plantations of bare-root oak stock have demonstrated somewhat limited success in terms of survival and especially in terms of early growth (e.g., Dixon et al., 1984; Stroempl, 1985).

Poor performance of hardwood plantations in general could be the result of failure to produce quality seedlings in the nursery and/or failure to recognize the quality seedlings that are produced. Early recognition of seedling quality is still considered a major problem in artificial regeneration

(Kormanik, 1988). Present nursery grading procedures usually involve evaluation of seedling quality on the basis of seedling height, root collar diameter, terminal bud condition, and shoot:root ratio (Venator, 1983; Duryea, 1984; Kormanik, 1988). The common emphasis on shoot morphology of seedlings has not consistently provided stock with uniformly good potential for survival and rapid growth after field planting (Kormanik, 1989; Schultz and Thompson, 1989). Recent studies by a number of researchers indicate that survival and shoot growth of transplanted seedlings may depend more on morphological characteristics of the seedling root system and the ability of the seedling to rapidly produce new roots (e.g., Farmer, 1975; Sutton, 1980; Burdett et al., 1983; Kormanik et al., 1988; Rietveld and van Sambeek, 1989; Barden and Bowersox, 1989). A more thorough discussion of root growth potential per se is given in Appendix A. From the work of some of these researchers (particularly studies done with hardwood seedlings) it appears that the potential for new root production by a seedling may be determined by the presence of an adequate system of relatively large permanent lateral roots, which provide sites for initiation of new roots (Schultz and Thompson, 1987).

It has been suggested that grading criteria applied in the nursery should include at least a morphological assessment of seedling root system quality (e.g., Duryea, 1984), although the desired root morphology for seedlings is not generally agreed upon (perhaps because it varies considerably depending on seedling species and stock type being considered). It does appear that for a number of species, the framework of the "permanent" root system of a tree is determined early in the seedling stage (e.g., Lyford, 1980; Coutts and

Lewis, 1983) and therefore it should be possible to recognize and evaluate the "permanent" root systems of one- or two-year-old bare-root stock.

In addition to physiological and morphological seedling attributes, rate and form of root development after outplanting depend on the interaction of the seedling with the environment of the planting site, particularly with respect to soil properties (Sutton, 1980; Burdett et al., 1983; Duryea, 1985; Barnett, 1988). Although the ability of the seedling to acquire water and nutrients depends on the seedling root system, the presence of water and mineral nutrients depends largely on soil properties and the physiography of the planting site. Because root habit is responsive to different environmental (e.g. soil) conditions, there is a need to identify soil factors that are critical to seedling performance (Sutton, 1980; Duryea, 1985).

This study was undertaken to analyze the performance of one-year-old northern red oak seedlings with graded root systems of varying quality on a number of different sites. The main objectives of this research were to determine if seedlings with high quality root systems at the time of transplanting have a significant advantage in terms of adaptation to a new soil environment after they are transplanted, and whether they maintain this advantage regardless of the characteristics of the planting site. This project was done in conjunction with a larger regional study evaluating performance of bare-root red oak, white oak, and black walnut seedlings in six central states (Schultz and Thompson, 1987; Schultz, 1989).

The results of this study will be presented in two parts. The first part contains an analysis of the survival and growth of oak seedlings with respect to root grade (numbers of large first-order lateral roots) at the time of outplanting. The second part discusses the performance of the same seedlings with respect to site factors, particularly soil properties.

PART I. SURVIVAL AND GROWTH OF RED OAK SEEDLINGS WITH RESPECT TO ROOT GRADE

INTRODUCTION

Grading seedlings on the basis of shoot characteristics (e.g. height and diameter), particularly for bare-root hardwood seedlings in the central states, has not consistently provided high quality transplant stock. A number of workers have suggested the importance of planting large seedlings, and have noted that a large root system is critical for seedlings to compete successfully (e.g., Sander, 1977). A major goal of this study was to evaluate the effectiveness of using root system morphology to ensure selection of high quality red oak seedlings for outplanting. An ideal morphological root system criterion would be an easily quantifiable and relatively permanent feature (likely to survive lifting and planting processes, and remain for some time after outplanting), biologically significant (in terms of seedling survival, growth, and ability to "capture" the site), and allow rapid, easy (and therefore inexpensive) assessment in routine nursery grading operations.

Earlier work with sweetgum (*Liquidambar styraciflua*) by Kormanik (1986) suggested that lateral root morphology could affect early plantation establishment and growth, and might provide a major identifying characteristic of superior seedlings. Kormanik "graded" one-year-old bare-root seedlings according to the number of permanent lateral roots present. First-order lateral roots that were rigid, suberized, and at least one millimeter in diameter proximal to the taproot were considered permanent. Seedlings were separated into three root grade groups based on numbers of permanent first-order lateral roots: those with 0 to 3, 4 to 6, and 7 or more large lateral roots. Kormanik's root grading approach was adopted with very slight modifications for this study of northern red oak seedlings.

LITERATURE REVIEW

Seedling Root System Development

The radicle of an oak seedling forms from an embryonic root apex and is usually well developed by the time the acorn is ripe (Sutton, 1980b). After the radicle emerges from the seed, it develops into the primary root (or taproot) of the seedling. This root is strongly geotropic, and elongates rapidly (e.g. 1 cm/day) for two to three weeks after germination using food reserves stored in the acorn (Lyford, 1980; Sutton, 1980b; Thompson and Schultz, unpublished). First order lateral roots (those that arise from the primary root or taproot) form very early in seedling development, arising acropetally at some distance from the root apex (McCully, 1975). The periderm of the primary root is already beginning to suberize when first-order laterals appear.

The rate of taproot elongation is reduced when the first flush of shoot growth and expansion of the first leaves takes place (Webb and Dumbroff, 1978; Thompson and Schultz, unpublished). Subsequent "flushes" of root growth activity in oak seedlings (elongation and diameter growth of the taproot, growth of first-order laterals, and elaboration of second- and higher-order laterals) depend largely on current photosynthate from the most recent shoot flushes (Dickson, 1991). Many studies have indicated that seedling growth in both conifers and hardwood species follows such a "rhythmic" or "episodic" growth pattern (Lyr and Hoffman, 1967; Borchert, 1973, 1975; Drew and Ledig, 1980; Reich et al., 1980; Langlois et al., 1983). Episodic growth patterns are characterized by alternating periods of active growth and periods of "rest" staggered such that most active root growth occurs when the shoot is not expanding and vice versa. These growth patterns result from the distribution and allocation of carbon to different plant parts (e.g. Dickson and Tomlinson, 1989). Episodic growth in red oak is most pronounced in seedlings and stump sprouts, while mature trees revert to fixed (a single flush of growth from one preformed bud) growth (Dickson, 1991).

As individual first-order laterals arise from the primary root, a small number have relatively large primary xylem diameters, exhibit fast growth, and have a greater chance of undergoing secondary thickening to become permanent members of the growing root system (Coutts, 1987). On seedlings grown in a nursery, a large proportion of these dominant first-order roots are discernible very early in seedling development (ca. 2 months after germination, Thompson and Schultz, unpublished), and their dominance persists unless the roots are damaged (Coutts, 1987). For seedlings that will be transplanted at 1 year of age, these large, suberized first-order lateral roots form the structural root system of the outplant.

Researchers working with a number of species maintain that mature trees typically have on the order of 3 to 11 large first-order lateral roots that formed within the first 3 to 7 years of seedling life (Lyford, 1980; Coutts and Lewis, 1983; Coutts, 1987; Gilman, 1990). On the other hand, there is wide agreement that second- and higher-order roots are very ephemeral features (e.g., Lyford, 1980; Fogel, 1983). Particularly for bare-root seedlings, the "robust" woody first-order lateral roots are the most likely to survive exposure and dessication during lifting, grading, packing, storing, shipping and planting processes (Insley and Buckley, 1985; Schultz, 1989). The first-order lateral roots which have undergone secondary thickening are most likely to be fairly permanent features of the growing tree.

Biological Significance of Large First-Order Lateral Roots

The immediate importance of structural first-order roots is probably twofold, involving direct absorption of water and mineral nutrients as well as providing sites for initiation of new higher-order roots. Even in the presence of unsuberized higher-order roots on seedlings and trees that have not been transplanted, relatively large woody roots can play a significant role in water and mineral absorption (Kramer and Bullock, 1966). Kramer and Bullock estimated that water absorption through suberized roots ranged from 60 to 96 % of the total water uptake for 26- to 34-year-old trees. They speculated that woody roots might be able to absorb water through lenticels, in crevices associated with branch roots and/or at sites of breaks or wounds in the "bark" (Kramer and Bullock, 1966). In the absence of higher-order roots that have died as a result of handling, suberized roots may provide the only source of water and mineral nutrition for transplanted seedlings until higher-order roots have been initiated and elongate.

Work by Stone and others (1962) with conifers showed that new root growth within the first month after transplanting was primarily due to extension of preexisting first-order lateral roots (see also Appendix A). They hypothesized that a longer time was necessary for initiation and subsequent elongation of new roots than was required for elongation of roots that were already present. This was also the case for the red oak seedlings used in this study, as described in Appendix A. It appears that immediate expansion of the seedling root system after transplanting depends directly on the presence of the relatively permanent first-order lateral root system.

The degree of structural root system development (or number of large first-order lateral roots) is often positively correlated with a number of other seedling parameters, including other root system biomass measures (based on weight), and root collar diameter (Khajjidoni and Land, 1988; South et al., 1988; Feret, unpublished).

While the importance of a large "root mass" for seedling establishment has been recognized (e.g., Sander, 1977; Duryea, 1984), a simple means of quantifying "root mass" on the basis of a permanent seedling characteristic for bare-root transplant stock has only recently been suggested. A small number of investigations has focused on the relationship between numbers of large first-order lateral roots on hardwood bare-root seedlings at the time of transplanting and subsequent seedling performance (Kormanik, 1986, 1988, 1989; Kormanik and Ruehle, 1989; Schultz and Thompson, 1990; Feret, unpublished). Under controlled growing conditions, Feret (unpublished) noted a strong positive correlation between numbers of permanent first-order lateral roots and new shoot growth. Kormanik (1986) reported significant differences and positive correlations between numbers of permanent first-order lateral roots of sweetgum seedlings and survival, height, and root collar diameter at the end of the first growing season in the field. In addition, stem dieback was significantly negatively correlated with numbers of large lateral roots. After five growing seasons, grade 1 seedlings (with 7 or more permanent lateral roots) had double the volume per stem and 30% greater survival compared to grade 3 seedlings (0 to 3 permanent laterals) (Kormanik, 1988). Based on strong correlations between permanent first-order lateral roots and seedling performance, Kormanik and coworkers contend that numbers of permanent first-order lateral roots are among the best predictors of field performance and competitive ability of outplanted seedlings (Kormanik et al., 1988; Kormanik and Ruehle, 1989).

Intuitively, vigorous root growth is needed to sustain vigorous shoot growth, so that a large network of permanent roots capable of supporting initiation of new roots and exploitation of a relatively large volume of soil should confer an advantage in terms of competitive seedling shoot growth.

Practical Assessment

Morphological measurements of seedlings have traditionally been used in routine nursery grading procedures because such measurements are usually quick and relatively simple to make (Racey, 1985; Thompson, 1985;). To best predict seedling success and competitive ability, however, the feature graded should be reliably and strongly related to performance after outplanting (in other words, the feature should have physiological significance). Morphological grading criteria work particularly well if it is possible to identify a critical threshold for optimal performance (e.g., Duryea, 1985). Because shoot morphology (especially seedling height) is not consistently related to field performance for bare-root hardwoods in the central states, establishment of root grading on a morphological basis in the nursery industry has been proposed as an inexpensive means of identifying potentially successful seedlings (and culling those that are not) before they are outplanted.

MATERIALS AND METHODS

General Information

The seedlings used for this study were selected from nursery-run northern red oak 1-0 bare-root stock at the Iowa Department of Natural Resources State Forest Nursery in Ames. These seedlings were grown in the nursery during the 1986 growing season, lifted in the spring of 1987, and cold-stored in plastic bags approximately 1 month before grading and planting. The seedlings were not undercut or top-pruned prior to lifting.

Seedlings were removed from cold storage for a brief time to count the number of lateral roots greater than 1 mm in diameter proximal to the taproot and measure the length of the taproot on each seedling. Seedlings were divided into three groups according to number of large (>1 mm) first-order lateral roots: grade 1 seedlings with 0 to 4 large laterals, grade 2 seedlings with 5-9 large laterals, and grade 3 seedlings with 10 or more large laterals. Seedling root grade group was identified by a colored tag on each seedling which also indicated specific root number and taproot length for individual seedlings. Measurements were made on 840 seedlings. Seedlings were returned to cold storage in plastic bags until planting.

Eight-hundred ten of the graded seedlings were outplanted 30 April and 1 May 1987. The remaining 30 seedlings were used in the root growth potential test described in Appendix A.

Ninety trees (30 of each root grade group) were randomly planted on nine plots distributed among three locations in central Iowa (Figure 1). Three plots were located southwest of Boone at the Fick Observatory (Boone County; Section 12, T. 83 N., R. 27 W.). Five plots were located south of Rhodes at Iowa

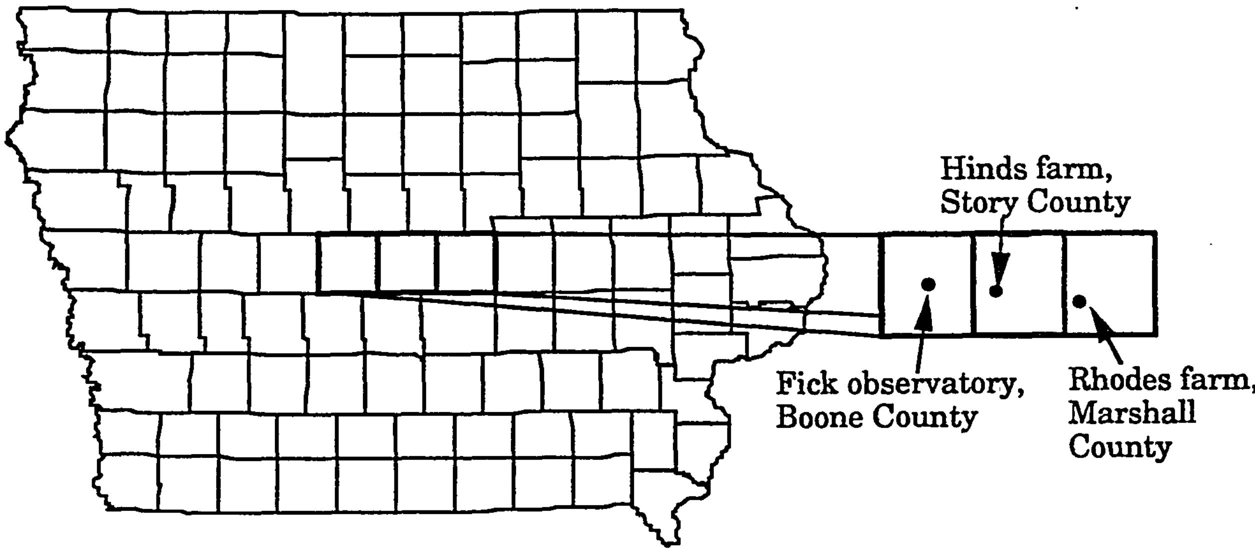


Figure 1. Location of outplanting sites in central Iowa

State University's "Rhodes Farm" (Marshall County; Section 18, T. 82 N., R. 20 W.). One plot was located at the north edge of Ames on the Hinds farm (Story County; Section 26, T. 84 N., R. 24 W.). No site preparation was done before seedlings were planted. Trees were planted at a 4' by 5' spacing in 12-inch deep holes dug using a two-person power auger with an 8" diameter bit. (Two plots were planted using shovels--the plot on the Hinds farm and the "R1" plot at Rhodes). Approximately one week after planting a 2% solution of glyphosate herbicide ("Roundup") was applied to control weeds in a two foot diameter circle around each seedling. A mixture of Poast and Fusilade (approximately 1.5%) was applied around each seedling early in July, 1987, to control grass competition. Due to prolonged drought, six trees on each plot were watered in August 1988 to ensure adequate survival to excavate that number of seedlings in spring 1989 (randomly selected seedlings which were then excavated in 1989).

Field Measurements

Initial height and diameter measurements were made in the spring of 1987 after seedlings were outplanted. Annual counts of survival and measurements of height and diameter growth for all seedlings were made in February through May, 1988 (first-year growth), November, 1988 (second-year growth) and November, 1989 (third-year growth). Measurements of height were made to the nearest 0.5 cm. Diameter was measured to the nearest 0.1 mm using mechanical or electronic calipers and measuring the largest viable stem just above the root collar (or near the soil line if the root collar was not visible). Survival percentages were calculated as the number of trees remaining of the original thirty trees for each root grade group less the number of trees excavated up to the time of each annual measurement. The fifth plot at Rhodes was included in survival counts and field measurements for only the first two years.

Measurements of Harvested Trees

Beginning in the fall of 1987, six randomly selected trees (two of each root grade group) from eight of the plots were excavated each of three years for more detailed analysis (October-November, 1987, June-July, 1988, and May-June, 1989). In 1987, seedlings were excavated by hand using small mason's trowels and taking care to preserve as much of the seedling root system as possible (Figure 2A). In 1988 and 1989, a large hydraulic tree spade (Vermeer Model TS-44) was used on six of the plots to lift a 1-m diameter by 1-m deep "cone" of soil centered on the excavated seedling (Figure 2B). The soil was then removed gradually using mason's trowels, again taking care to preserve the seedling root system (Figure 3). Two plots were not accessible with the tree spade and seedlings on these plots were excavated by hand as done in 1987 (Rhodes farm, "R2" and "R3"). Seedlings excavated in 1989 had been randomly selected late in the 1988 growing season and watered (approximately 9 gallons H_2O per seedling, 20 August 1988). After excavation, seedlings were cold stored in plastic bags with a small quantity of water until measurements were made. Seedlings were not excavated from the fifth plot at the Rhodes farm.

Excavated seedlings were measured to determine shoot height, diameter just above the root collar, crown depth (distance along stem between highest viable bud and lowest viable buds or leaves), length of taproot, length of longest lateral root, width of rootmass, number of first-order lateral roots

Figure 2. Excavation of seedlings

(A) Excavation by hand on plot H1 in 1987

(B) Excavation using Vermeer tree spade on plot F1 in 1988

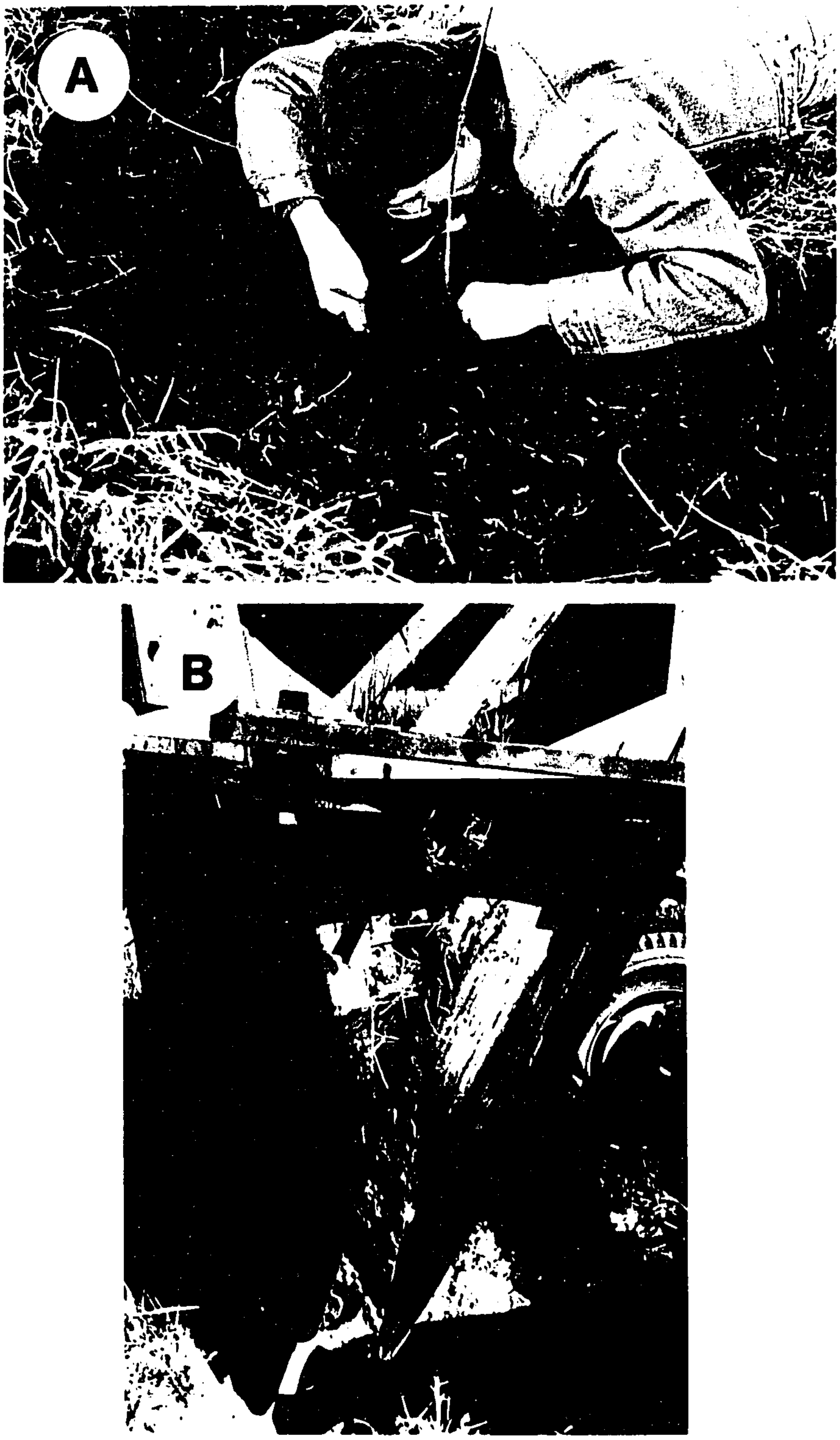
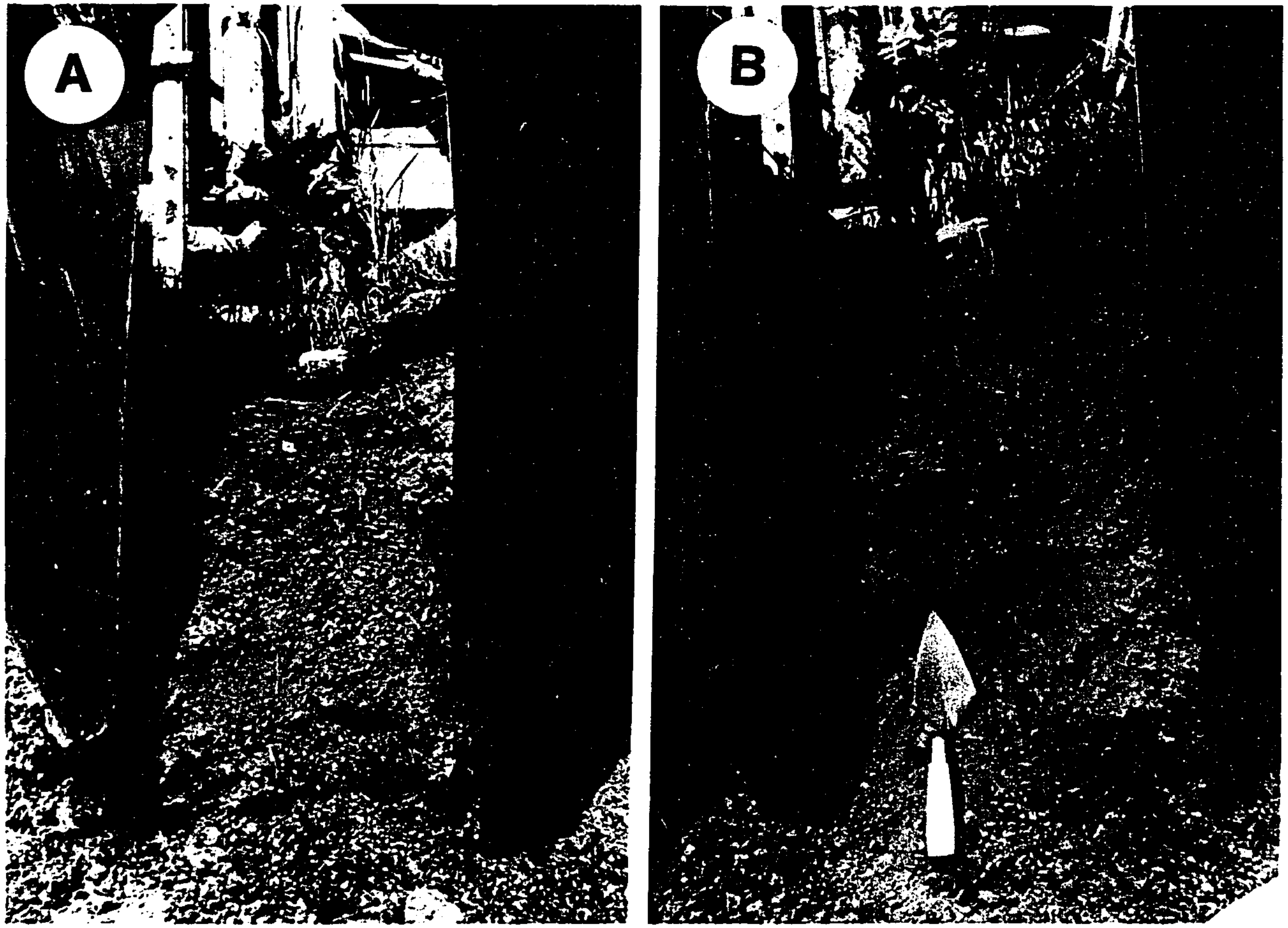

A
B

Figure 3. Excavation of seedling using Vermeer tree spade on plot F2 in 1989

(A) Removing soil material toward seedling root system

(B) Exposed root system of seedling in soil


A
B

greater than 1 mm in diameter proximal to the taproot, number of large first-order lateral roots that originated at or near the callus (formed at the lifting wound), and total numbers of first- and second-order lateral roots. After measurements were made, seedlings were photographed, and roots, stems, and leaves were separated and dried at 65 degrees C for at least 24 hours. Dry weights were determined for leaves, stems, shoots (leaves + stems), taproots, lateral roots, and total roots (taproots + laterals).

Data for field measurements and harvested trees were analyzed using the Statistical Analysis System (SAS Institute, 1985).

RESULTS AND DISCUSSION

Field Measurements

Seedling survival

Results of annual survival counts averaged over 8 plots are shown in Figure 4 and summarized in Table 1. Survival rates for all root grade groups were excellent for the first year (1987), with an overall mean of 96%. Numbers of surviving seedlings declined slightly to an overall mean of 88% in 1988. At the end of the third field season, however, significantly lower survival rates occurred among all three root grades, with an overall mean of 66%. Mortality was severe for seedlings that had four or fewer large first-order lateral roots at the time of transplanting: only 54% of grade 1 seedlings remained at the end of the 1989 growing season, compared with more than 70% for the grades 2 and 3 seedlings. After consideration of plot differences (discussed in Chapter 2), variation in survival which could be attributable to root grade was most significant in 1989. Results of analysis of variance and calculation of the least significant difference between these means indicated that grade 1 seedlings were statistically different from grades 2 and 3, but that grades 2 and 3 were not significantly different from each other. This information is also summarized in Table 1 Probably the largest single factor contributing to the increase in mortality in 1988 and 1989 was a prolonged drought during much of the growing season during those years (below normal precipitation and above normal temperatures, see climatological summary in Appendix C).

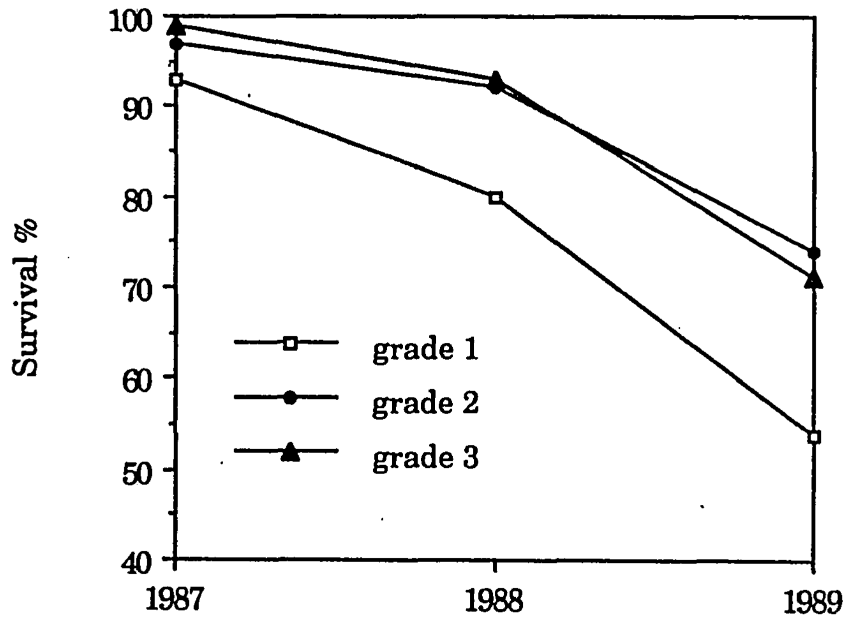


Figure 4. Average percentage survival for all seedlings for 3 years

Table 1. Summary of survival rates (percent) of root-graded red oak seedlings for three years after outplanting

Seedling Grade	Year 1987	1988	1989
1 (0-4 roots[a])	93	80	54
2 (5-9 roots)	97	92	74
3 (>10 roots)	99	93	71
Mean	96	88	66
LSD[b] (at .01 level)	8.9	15.2	12.1
Pr>F	0.15	0.05	<0.01

[a]Mean number of roots for grade 1 seedlings was 2.0, for grade 2 seedlings was 6.7, and for grade 3 seedlings was 12.5. These numbers approximated the median for the root grade groups, i.e. seedlings were evenly distributed within the groups.

[b]Least significance difference between mean survival values for root grade.

First-year survival (under nearly ideal conditions: see 1987 climatological data in Appendix C) in this study was not significantly affected by seedling root grade at the time of outplanting. This is similar to 5-year results reported by Olson and Hooper (1972) for red oak seedlings outplanted in North Carolina. These workers noted no significant differences in red oak seedling survival due to root collar diameter (often closely correlated with numbers of large first-order lateral roots), and a mean survival rate of 87%.

Under more stressful conditions in 1988 and 1989, seedling survival in this study was affected by initial root grade (and the resulting root:shoot ratio of the seedlings) in the second and third year after outplanting. Other researchers working with hardwoods have noted significant differences in survival among root graded seedlings, particularly under droughty conditions (e.g. Kormanik, 1988, with sweetgum seedlings). For a number of species, under less than ideal circumstances after transplanting, seedlings with greater numbers of large first-order roots and seedlings with larger root collar diameters have been reported to have significantly greater survival rates than seedlings with fewer roots or smaller root collar diameters (for example, South et al., 1985, with loblolly pine). Intuitively, under droughty conditions a seedling with a large root system would be better equipped to survive than a seedling with a small root system (Hobbs, 1984).

Seedling growth

Mean values for height and diameter characteristics of the three grades of seedlings at the time of outplanting (initial height and diameter) and at the end of the first, second, and third growing seasons after transplanting are shown in Figure 5 and given in Table 2. Significant differences in initial height occurred between grade 1 seedlings and the others. Height differences between grade 2 and grade 3 seedlings were also significant after the third growing season. Differences in seedling diameter were significant among all three seedling grades at each time of measurement. Mean values for incremental height and diameter growth are given in Table 3.

Height growth Differences in seedling height between root grades increased after each growing season, similar to results reported by Kormanik (1986) for sweetgum. In this study, however, the differences between height for grade 1 seedlings and the others increased over time (Figure 5) due largely

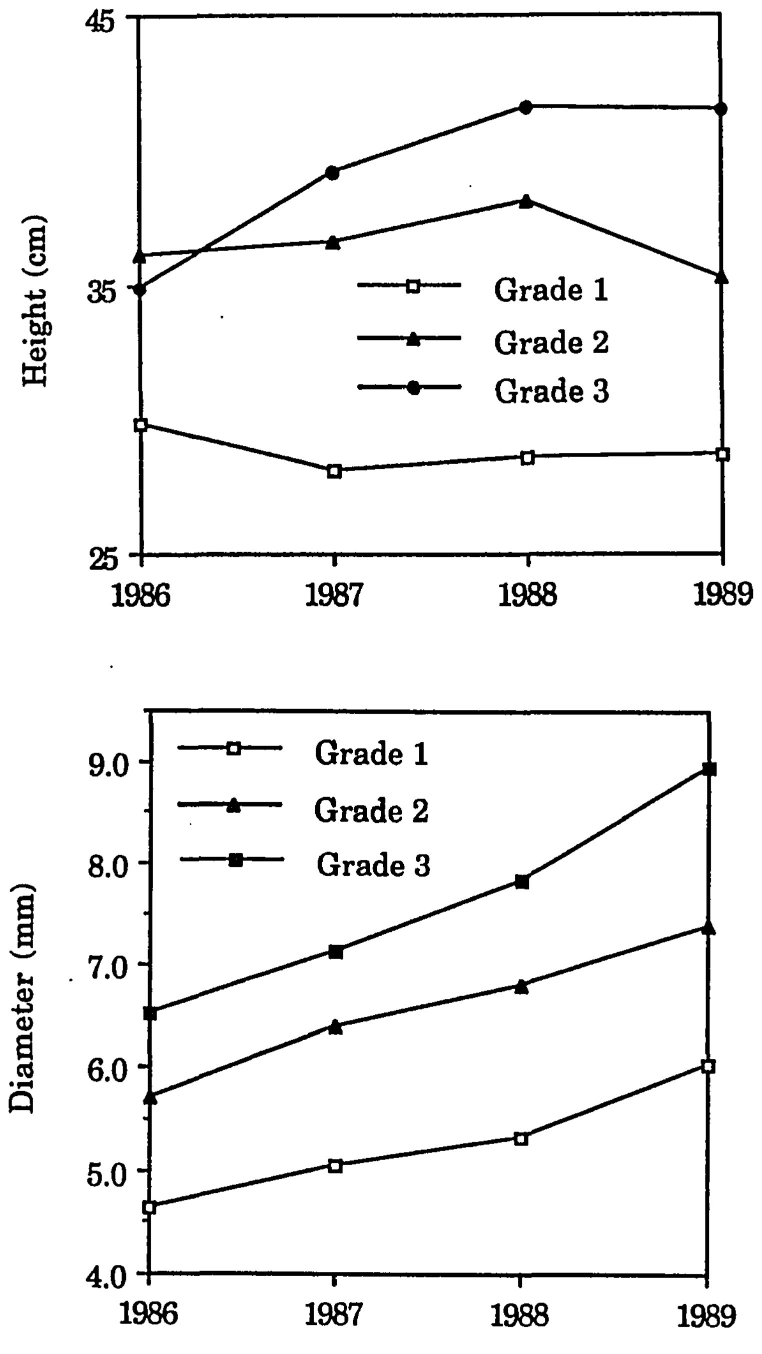


Figure 5. Average height and diameter for all seedlings for 3 years, by root grade

Table 2. Means for seedling height (cm) and diameter (mm) by root grade group

Root grade	Initial	First year	Second year	Third year
		Height		
1	29.8a[a] (n=271[b])	28.1a (254)	28.5a (210)	28.6a (120)
2	36.1b (265)	36.6b (259)	38.1b (233)	35.2b (154)
3	34.9b (272)	39.2b (268)	41.6b (238)	41.5c (152)
LSD[c]	3.7	3.5	4.9	5.2
		Diameter		
1	4.63a (271)	5.05a (254)	5.33a (183)	6.04a (120)
2	5.71b (265)	6.39b (259)	6.79b (203)	7.38b (154)
3	6.51c (272)	7.12c (268)	7.82c (208)	8.95c (152)
LSD	0.36	0.48	0.67	0.83

[a]Means within a column for a seedling characteristic with the same letter are not statistically different ($p < 0.01$) using the Type III MS for plot*root grade as an error term.

[b]Due to mortality and missing values, the number of seedlings for calculation of means is variable and is indicated in parentheses after the mean value.

[c]Least significant difference between two means ($p < 0.01$).

Table 3. Annual and cumulative incremental height (cm) and diameter (mm) growth by root grade group

Root grade	First year	Second year	Third year	Cum. (2 yrs)	Cum. (3 yrs)
		Height growth			
1	-2.1a[a] (254)	-0.02a (210)	-1.5a (119)	-2.4a (210)	-3.5a (120)
2	0.3a (259)	1.8b (233)	-2.9a (154)	1.9b (233)	-0.3a (154)
3	4.4b (268)	2.8b (238)	-0.01a (152)	7.0c (238)	8.8b (152)
LSD[b]	2.9	2.0	3.7	3.8	4.5
		Diameter growth			
1	0.35a (254)	0.27a (183)	0.53a (119)	0.66a (183)	1.17a (120)
2	0.64a (259)	0.57b (203)	0.46a (154)	1.20b (203)	1.78ab (154)
3	0.59a (268)	0.76b (208)	0.93a (152)	1.40b (208)	2.53b (152)
LSD	0.35	0.31	0.85	0.67	0.85

[a]Means within a column for a seedling characteristic with the same letter are not statistically different ($p < 0.01$) using the Type III MS for plot*root grade as an error term.

[b]Least significant difference ($p < 0.01$).

to negative height growth of grade 1 trees (a result of mortality of taller trees within that seedling group, as well as dieback of stems).

In general, the height growth curves for all three seedling grades were relatively flat, and the mean height for grade 3 seedlings at the end of the third year was only 41.5 cm (although the range is extreme, from 0 to 102 cm for grade 3 seedlings). Poor performance of all three seedling grades in terms of average height growth corroborates results of other workers. As Dickson (1991) indicates, under adverse conditions, shoot flushing (top growth) stops and photosynthate is reserved (presumeably in the roots). Olson and Hooper (1972) similarly reported significant differences in height for graded red oak seedlings after 2 and 5 years in the field, and also concluded that height growth of all seedlings in their analysis was inadequate. A number of factors may have contributed to poor overall height growth in this study: damage from insect and animal activity (grasshopper damage was noted in all years of the study, deer were frequently seen at all sites, cattle were occasionally present on one plot at the Rhodes farm, and humans did in fact mow down an entire plot at Rhodes and some trees at Hinds), drought, and drought exacerbated by intense weed competition (weeds were not controlled in 1989). Other workers have noted detrimental effects on survival and height growth due to these factors (e.g., Olson and Hooper, 1972; Gjerstad et al., 1984; Hobbs, 1984; Stroempl, 1989; and Wright et al., 1989).

Diameter growth Initial differences in seedling diameter between root grade groups are magnified after 3 years in the field (Figure 5). In fact, the average diameter of grade 1 seedlings 3 years after transplanting is still less than the initial average diameter of the grade 3 seedlings. However, a significant difference in diameter growth rates (incremental data in Table 3) occurred only in the second year after transplanting between root grade 1 versus grades 2 and 3. Cumulative 3-year diameter growth increment data indicate a significant difference between root grade 1 and root grade 3 (grade 2 is not significantly different than either 1 or 3). Initial seedling diameter has been found to be strongly correlated with survival and height growth for at least 10 years after transplanting for a number of species (South et al., 1985; Stroempl, 1985; Thompson, 1985; Rietveld and van Sambeek, 1989).

Relationships among height and diameter characteristics The MANOVA procedure of SAS (1985) was used to generate a partial correlation matrix for all values of the variables for which means are presented in Tables 2 and 3. Root grade (actual number of permanent first-order lateral roots), initial height, and initial diameter are significantly ($p < 0.01$) and positively correlated. First year height and diameter are significantly and positively correlated with each other and with initial seedling parameters. First year incremental height growth was correlated with root grade ($r^2 = 0.20$, $p < 0.01$) and initial diameter ($r^2 = 0.20$, $p < 0.01$). However, first-year incremental height growth was negatively correlated with initial height ($r^2 = -0.14$, $p< 0.01$, indicating that the tallest trees exhibited more negative growth or dieback, especially for grade 1 trees). This strongly suggests that morphological grading systems which include assessment of seedling roots systems would be better predictors of seedling field success than the common approach of grading based solely on height. First year incremental diameter growth was not significantly correlated with any initial seedling characteristics, but was strongly and positively correlated with first-year height growth ($r^2 = 0.34$, $p <$

0.01). Second-year heights and diameters were positively correlated with initial and first-year measurements. Incremental height and diameter growth in the second year were only significantly correlated with each other ($r^2 = 0.47$, $p < 0.01$). Third-year height and diameter were again significantly and positively related to previous measures. Third-year incremental height growth was negatively correlated with previous measures (e.g. negative growth or virtually no growth in the third year). Third-year diameter growth was not significantly correlated with any previous measures. Cumulative 3-year height ($r^2 = 0.11$) and diameter ($r^2 = 0.10$) growth were positively correlated with root grade ($p < 0.05$). However, cumulative 3-year height growth was negatively correlated with initial height ($r^2 = -0.30$, $p < 0.01$) and cumulative 3-year diameter growth was negatively correlated with initial diameter ($r^2 = -0.14$, $p < 0.01$).

Measurements of Harvested Trees

Mean values for characteristics measured on harvested trees in 1987, 1988, and 1989 for each root grade group are presented in Table 4. Means in 1987 were based on a sample size of 16 trees per root grade group, 12 trees per group in 1988, and 16 trees per group in 1989. Harvested trees represented a randomly selected subset of the trees measured each year in the field, although harvested seedlings had somewhat higher mean heights and diameters within each root grade group when compared with overall means (compare data in Tables 2 and 4, first year =1987, second year=1988, etc.). This is probably due to a combination of random sampling effects (particularly for the grade 2 seedlings which are larger than the overall mean for that

Table 4. Means for characteristics measured on excavated trees

Characteristic	Root grade group 1	2	3	LSD[a]
		1987 (n=16 for each mean)		
Original root grade	1.5a[b]	6.5b	13.1c	2.8
Height	31.7a	48.7b	48.8b	10.8
Crown	13.4	39.8	22.8	x
Diameter	6.4a	8.2b	9.1b	1.7
Taplength	22.6	21.6	21.2	6.3
Longest lateral	37.2	42.4	55.2b	21.9
Width roots	31.0a	42.0ab	51.2b	19.6
New root grade	4.5a	10.2b	15.4c	3.7
Total 1st order lats	19.2a	26.1ab	31.1b	10.6
Callus roots	3.3	3.1	3.0	2.6
Total 2nd order lats	99a	193ab	203b	97
Dry wt. leaves	x	x	x	x
Dry wt. stem	3.0a	6.9b	6.3b	3.6
Dry wt. tap	7.0a	11.1ab	12.8b	4.5
Dry wt. lats	1.5	3.3	4.3	2.9
Dry wt. shoot	3.0a	6.9b	6.3ab	3.6
Dry wt. root	8.3a	14.4ab	17.2b	7.0
		1988 (n=12 for each mean)		
Original root grade	2.7a	6.7b	13.2c	2.0
Height	36.7	46.7	48.4	15.7
Crown	15.3	19.9	25.3	14.1
Diameter	6.4a	8.1ab	8.8b	1.71
Taplength	20.6	21.0	20.5	3.3
Longest lateral	40.7	47.6	47.3	21.8
Width roots	28.4a	35.4ab	50.8b	19.3
New root grade	6.1	10.7	16.5	5.5
Total 1st order lats	18.6a	23.8ab	28.8b	9.4
Callus roots	3.3	3.7	3.6	2.1
Total 2nd order lats	205	255	307	171
Dry wt. leaf	2.8	4.6	5.5	3.4
Dry wt. stem	4.0a	7.4ab	9.2b	4.6
Dry wt. tap	8.0a	11.2ab	14.5b	6.4
Dry wt. lats	2.1	2.9	6.3	4.4
Dry wt. shoot	6.7a	12.0ab	14.7b	7.2
Dry wt. root	10.0a	14.1ab	20.8b	9.8

[a]Least significant difference between two means at 0.01 level using Type III MSE for plot*root grade.

[b]Numbers in the same row followed by the same letter are not significantly different.

Table 4. (Continued)

Parameter	Root grade group 1	2	3	LSD
		1989 (n=16 for each mean)		
Original root grade	2.0a	6.8b	12.0c	2.2
Height	31.4	47.9	46.2	21.3
Crown	9.3	18.9	22.7	14.9
Diameter	6.2a	7.9b	8.6b	1.6
Taplength	20.4	20.2	18.8	3.0
Longest lateral	37.9	51.2	47.4	15.6
Width roots	41.5	51.9	59.7	20.5
New root grade	6.0a	11.4ab	15.9b	6.1
Total 1st order lats	19.6	26.1	30.3	13.2
Callus roots	3.2	4.1	4.4	2.2
Total 2nd order lats	147	260	313	215
Dry wt. leaf	2.3	2.8	4.3	2.4
Dry wt. stem	3.8	9.1	10.7	8.4
Dry wt. tap	7.6a	14.9ab	15.7b	7.9
Dry wt.laterals	3.0	6.0	7.6	5.4
Dry wt. shoot	6.1	11.9	15.0	10.2
Dry wt. root	10.6a	21.0b	23.3b	12.7

seedling grade) and differences due to method of measurement. For example, field measurement of height and diameter was often done just above the soil line, whereas measurement of height and diameter on harvested trees was always done just above the root collar. For seedlings that were planted with the root collar below the ground, a height difference of 6 cm (the average difference between the means in Tables 2 and 4) between the two measurements would not be unexpected. Significant differences between means for excavated seedlings ($p < 0.01$) among the root grade groups occurred for the following parameters: root grade, height (1987), diameter, width of rootmass (1988), new root grade, total first-order roots (1987 and 1988), total second-order laterals (1987), dry weight of stems (1987 and 1988), dry weight of taproots (1987 and 1988), dry weight of shoots (leaves + stems, 1987, 1988), and dry weight of roots (taproots + laterals).

Shoot characteristics

For harvested seedlings it is not possible to consider growth curves as discussed with respect to field measurements, since in this case measured seedlings were individuals that were destructively sampled in successive years (as opposed to repeated measurements on most of the same individuals). Results for seedling height and diameter measurements for the three years in which seedlings were harvested are shown in Figure 6. Differences in height between grade 1 seedlings and the others are statistically significant in 1987 ($p < 0.01$). Height differences between grade 1 and grade 3 seedlings are significant in 1988 ($p < 0.05$), and between grade 1 and grade 2 differences are significant in 1989 ($p < 0.05$). Results of diameter measurements similarly reflect most significant variation between grade 1 seedlings and the others, and a diameter distribution resembling that for seedlings measured in the field. In 1987, no statistically significant differences in crown size were found, probably due to great variation for crown depth measurements combined with a very small sample size (Figure 7). Leaves had already abscised from seedlings excavated in the fall of 1987, such that "mean" values for crown depth in 1987 were based on one measurement for grade one seedlings and 2 measurements for grades 2 and 3. However, trends for crown depth in

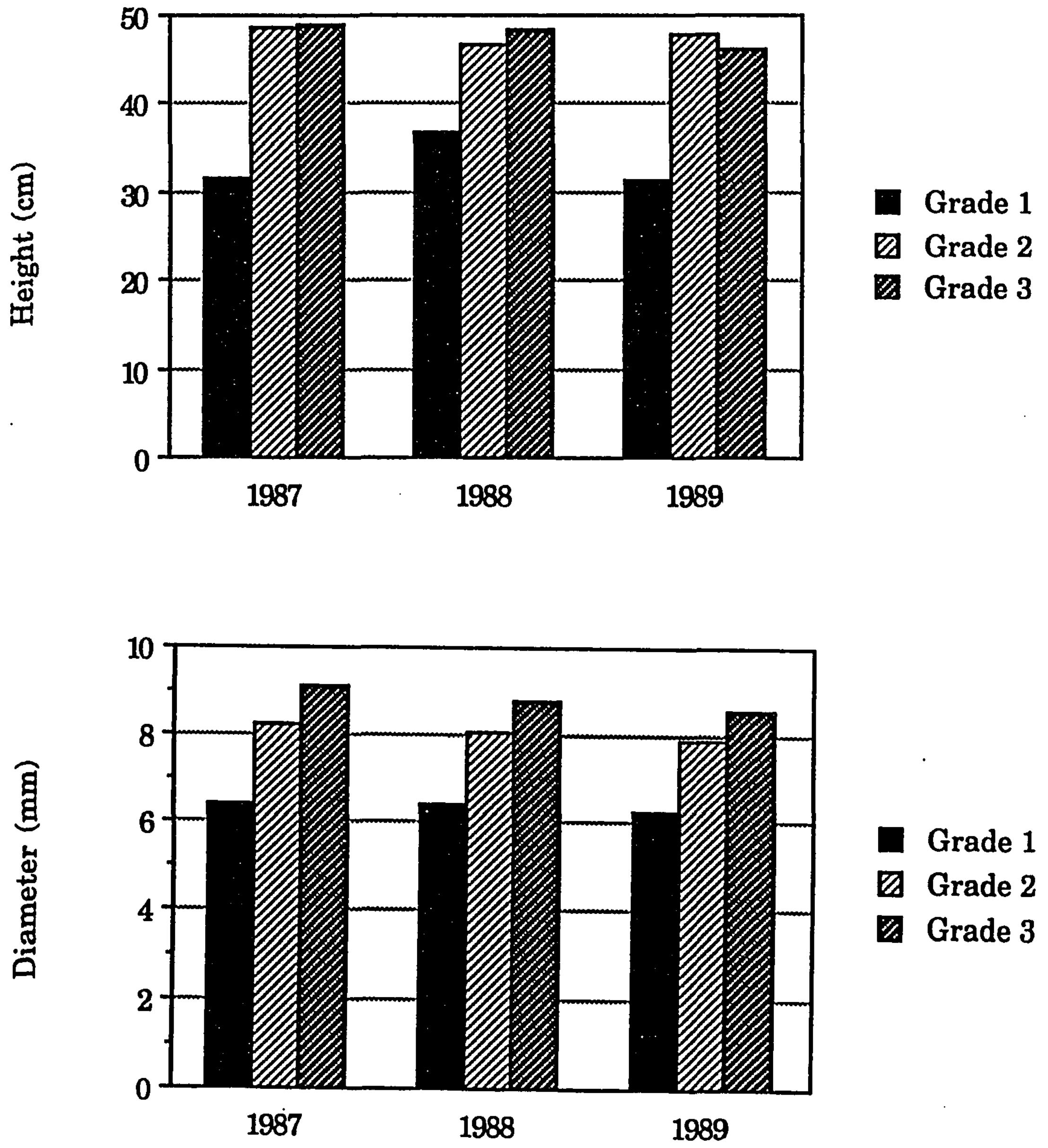


Figure 6. Average height and diameter for seedlings excavated in 1987, 1988, and 1989, by root grade

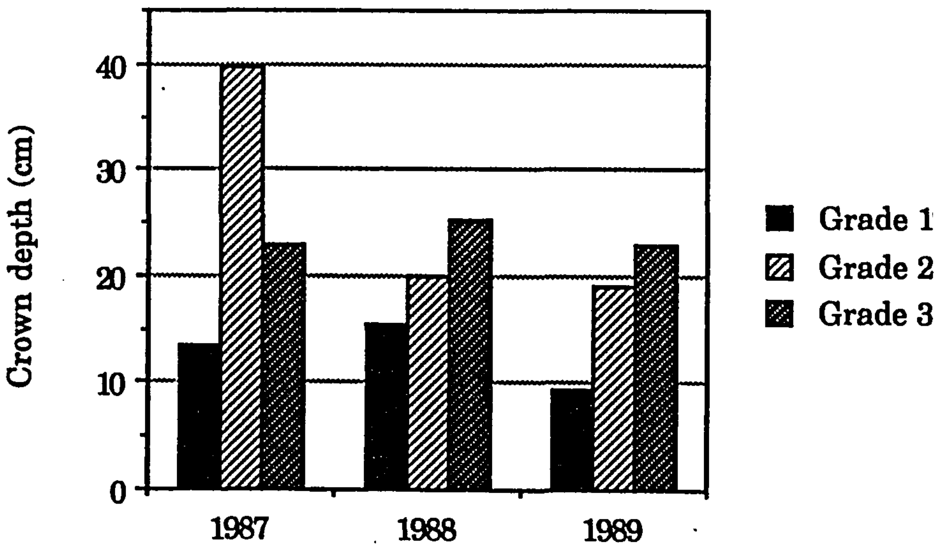


Figure 7. Average crown depth for seedlings excavated in 1987, 1988, and 1989, by root grade

1988 and 1989 are similar to those for height and diameter, and differences between grade 1 and grade 3 seedlings are significant ($p < 0.05$).

Average dry weight data for stems, leaves, and shoots are illustrated in Figures 8 and 9. The change in stem dry weights from 1987 to 1988 reflects part of the most important period of above-ground growth that occurred in this study (refer also to Figure 5). For most seedlings, this growth occurred in a single flush early in spring, in a bud that formed under nearly ideal conditions the previous growing season (see climatological data in Appendix C). There was, however, negative growth (grade 2) or very little aboveground growth (grades 1 and 3) in the spring of 1989. Again, seedlings produced only a single flush of growth, this time from a bud that formed under much less than ideal conditions the previous (1988) growing season. Comparison of average dry weight data for leaves in 1988 and 1989 corroborates field observations of fewer and smaller leaves on seedlings in 1989, due to fewer leaf primordia in the buds and probably also due to lack of moisture to support cell expansion in the leaves that did form. Differences in shoot dry weight between root grade groups 1 and 2 were significant ($p < 0.01$) in 1987, and between root grade groups 1 and 3 in 1988 (Table 4). Differences in shoot dry weight between grade 1 and grade 3 seedlings were significant in 1989 ($p < 0.05$).

<u>Root system characteristics</u>

Mean values for the original root grade of excavated seedlings are included in Table 4 to demonstrate that seedlings harvested in each year were

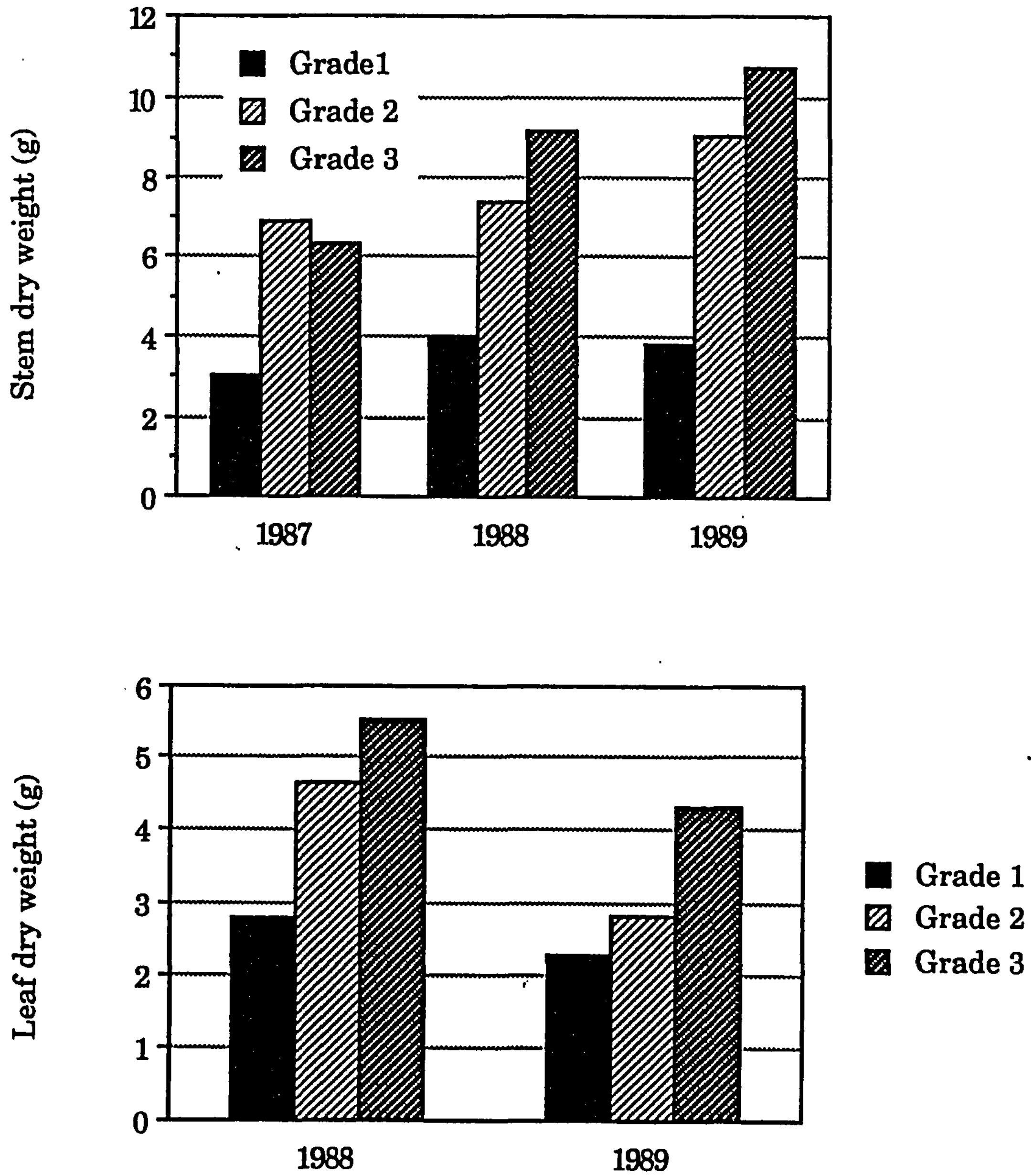


Figure 8. Average dry weights of stems and leaves for excavated seedlings, by root grade

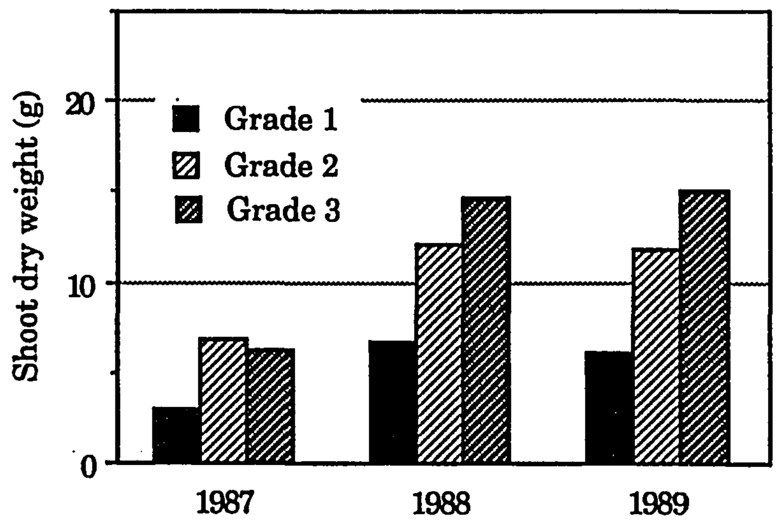
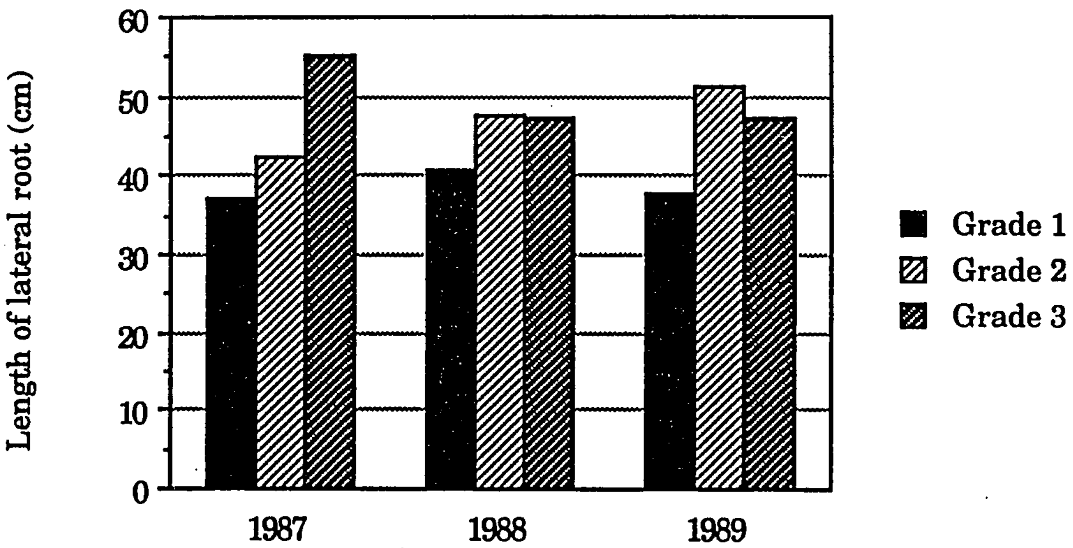


Figure 9. Average dry weights of shoots for excavated seedlings, by root grade

representative of their respective root grade group (e.g. that mean values approximated the median of each root grade group), and that the root grade groups were in fact statistically different from each other based on the random subsample for each year. Values for length of the seedling taproot ("Taplength") are shown in Table 4 to demonstrate that differences in seedling performance relative to root system characteristics were not due to cultural factors, for example, grade 3 seedlings having been lifted from the nursery with longer taproots as an explanation for their having more lateral roots. In fact, overall standard deviation in taproot length for excavated seedlings was very low (3.8 cm) and no significant differences occurred between seedling grades.

Length of the longest lateral and width of the rootmass for each seedling were measured to indirectly quantify the extent of soil exploration by seedling root systems. Mean values for these variables for the three root grade groups are shown in Figure 10. As Table 4 indicates, variation in length of the longest lateral between root grades was not significant at the 0.01 level, although differences between grade 1 and grade 3 seedlings in 1987 and between grade 1 and grade 2 seedlings were significant at the 0.05 level in 1988. The pattern for 1987 was as would be expected and similar to other characteristics shown in Figures 6, 8, and 9. However, the expected trend of consistently longer lateral roots in 1988 and 1989 was evident only for grade 2 seedlings. This may have been due to random sampling effects, or due to the method of excavation. Some lateral roots were cut off by the blades of the tree spade used on most plots in 1988 and 1989, or were broken off at the bottom of the "cone" of soil lifted by the spade (at a depth of about 1 m). Results of measurements of root mass



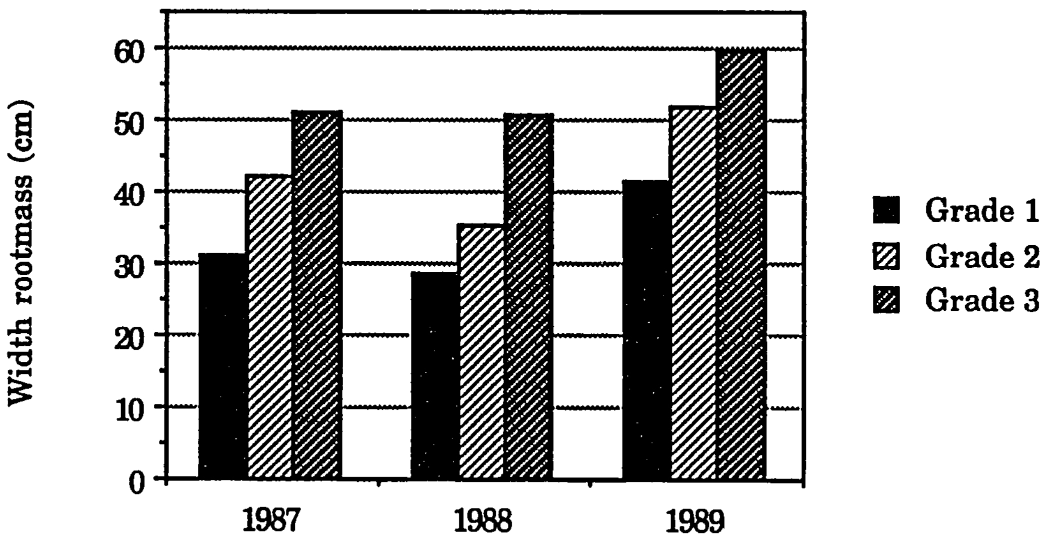


Figure 10. Average values for length of longest lateral and width of rootmass for excavated seedlings, by root grade

width indicated significant differences between grade 1 and grade 3 seedlings in 1987 and 1988 ($p < 0.01$) and 1989 ($p < 0.05$). Other workers have noted the length of lateral roots as a measure of soil volume exploited by roots (Stein, 1978; Faulkner and Fayle, 1979). In terms of soil volume exploited, seedlings that were outplanted with greater numbers of large lateral roots rapidly developed longer roots (on the average) and utilized a larger soil volume (more intensively and in three dimensions) than those with fewer roots, particularly in the first two years.

Values for new root grade (Table 4) indicate the number of large first-order lateral roots present on each seedling at the time of excavation. An increase of two to three roots from original to new root grade number was common to all root grade groups in all years. In most cases, the increase in root grade was due to the formation of callus roots near the lifting wound at the base of the taproot (also listed in Table 4). Callus roots are usually relatively permanent "branch" roots of the taproot and are characteristic of taprooted species which are transplanted as bare-root stock (Larson, 1970; Coutts, 1987). Lyford (1980) indicated that callus roots were more common than uninjured taproots even in red oak seedlings that were seeded in place. There appeared to be no significant differences in the ability to produce wound roots (see also a later summary of seedling morphology) that were attributable to the original root grade of the seedlings, although it is likely that the seedlings that were generally larger may have been able to produce them at less cost to the rest of the plant (e.g. produced from stored carbohydrate with less sacrifice in height growth in the first two years).

Mean values for total numbers of first-order lateral roots (Table 4 and Figure 11) include those first-order lateral roots that were smaller than 1 mm in diameter (and may be ephemeral). These numbers were significantly different ($p < 0.01$) between root grades 1 and 3 in 1987 and 1988, but were not significantly different between years within any root grade. Earlier work with red oak seedlings indicated that the total number of first-order lateral roots on a seedling is established very early in seedling development and does not change over time. Although some of the smallest first-order lateral roots may die and be sloughed off, they are replaced such that the total number remains nearly constant (Thompson and Schultz, 1989).

Mean values for total numbers of second-order lateral roots (also shown in Table 4 and Figure 11) range from 99 (for grade 1 seedlings in 1987) to more than 300 (for grade 3 seedlings in 1989). In 1987, differences between root grade 1 and 2 were significant ($p < 0.05$), and between 1 and 3 were significant ($p < 0.01$). No significant differences were computed for 1988, although differences between grade 1 and grade 3 were significant ($p < 0.05$) in 1989. Again, many of the second-order roots are ephemeral, but it appears that seedlings with greater numbers of permanent first-order lateral roots at the time of outplanting have more sites for initiation of second-order lateral roots, especially in the critical first year after outplanting.

Dry weight data for seedling taproots and lateral roots corroborate other evidence of most significant differences between grade 1 and grade 3 seedlings (Table 4 and Figure 12). Variation in taproot dry weights between grades 1 and 3 seedlings were significant ($p < 0.01$) all three years. Differences between grades 1 and 2 were significant ($p < 0.05$) in 1989. Variation in

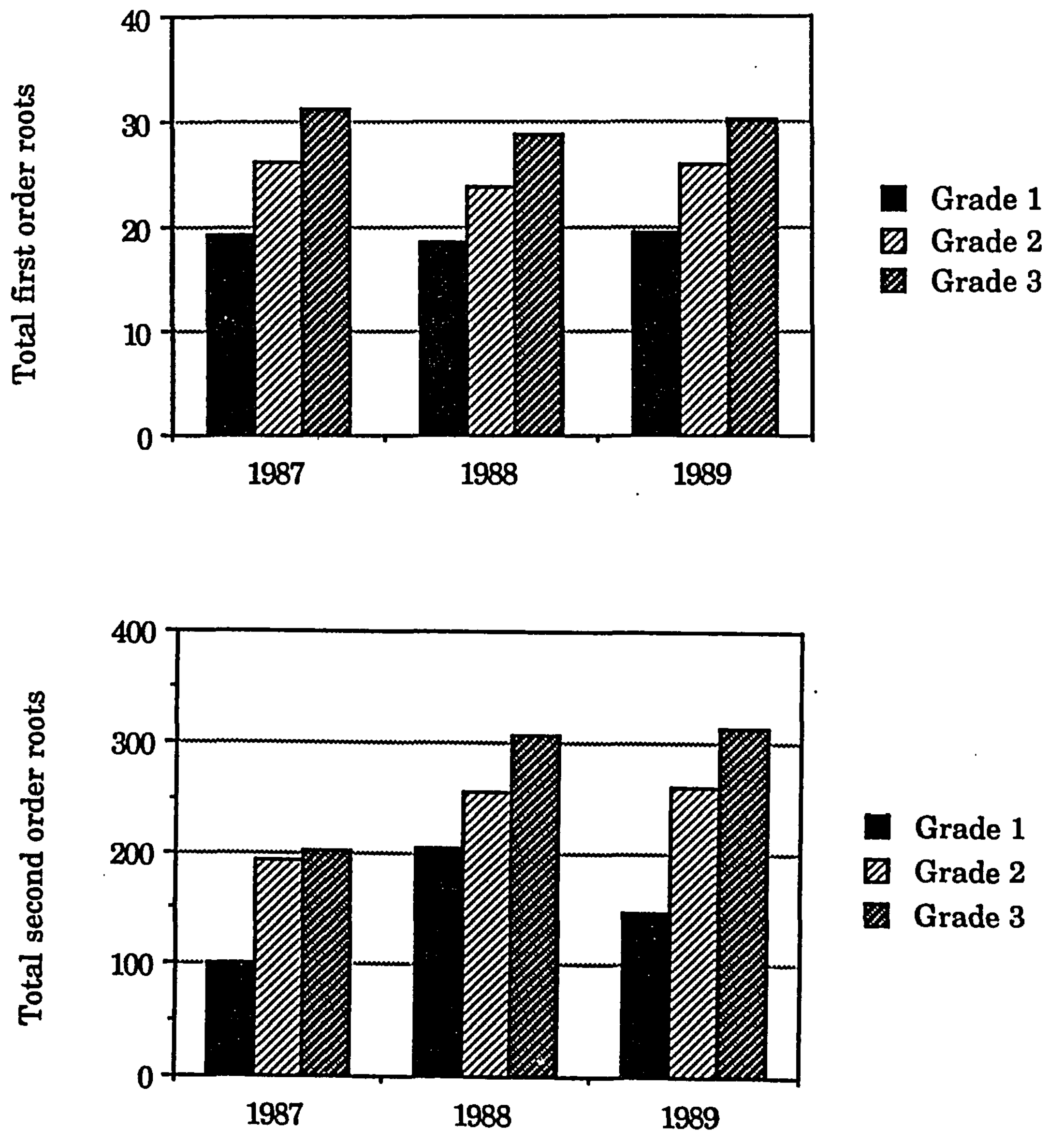


Figure 11. Average values for total numbers of first- and second-order lateral roots for excavated seedlings, by root grade

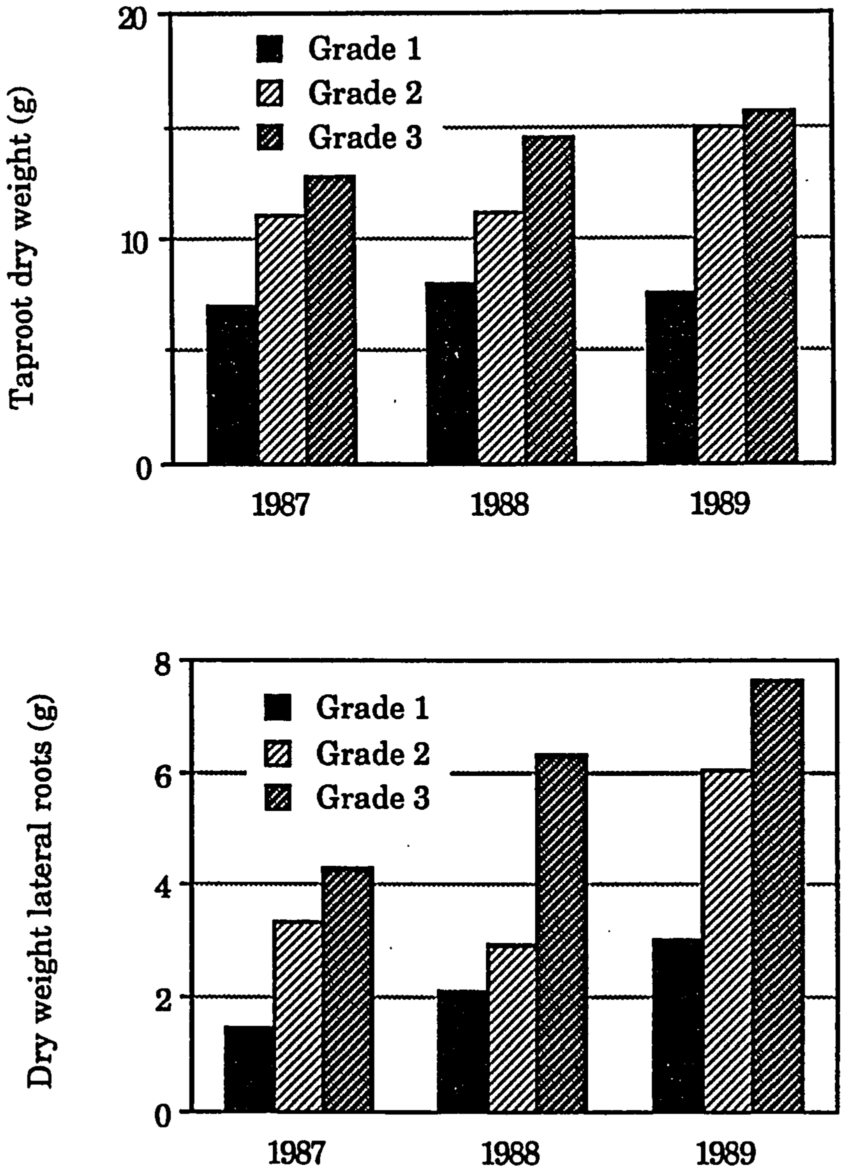


Figure 12. Average dry weights of taproots and lateral roots for excavated seedlings, by root grade

lateral root dry weights for grade 1 versus grade 3 seedlings were significant ($p < 0.05$) in all three years, and between grades 2 and 3 seedlings in 1988. Differences in total root dry weight (Figure 13) for grade 1 and grade 3 seedlings were significant ($p < 0.01$) for all three years. Trends over time suggest only slight changes in taproot dry weight during the course of the study. Since little variation was observed in length of the taproot between root grades or between years, much of the difference that did occur was probably due to diameter growth of seedling taproots. In addition, since seedlings were excavated late in the fall of 1987 and then again late in the spring of 1988, less dramatic change in dry weight occurred between 1987 and 1988 than between 1988 and 1989 (particularly for grade 2 seedlings).

Relationships among characteristics measured on harvested seedlings

The MANOVA procedure of SAS was used to generate partial correlation matrices for all variables measured in 1988 and 1989 for which means are presented in Table 4 (missing values for some variables prohibited doing this analysis for 1987 data). For trees excavated in 1988, original root grade was positively correlated with the following seedling characteristics at the time of excavation: diameter ($r^2 = 0.62$, $p < 0.01$), new root grade ($r^2 = 0.66$, $p< 0.01$), total first-order lateral roots ($r^2 = 0.52$, $p < 0.05$), and stem, taproot, lateral root, and total root dry weights ($r^2 = 0.44$ to 0.56, $p < 0.05$). These relationships suggest that root grade might be a good indicator of potential for competitive seedling growth. However, relationships between these variables were not significant in 1989. This could have been due to the effects of ongoing drought or due to random sampling error. As expected, significant relationships between height and crown depth ($r^2 = .60$, $p < 0.01$), diameter ($r^2 = 0.52$ to 0.69,

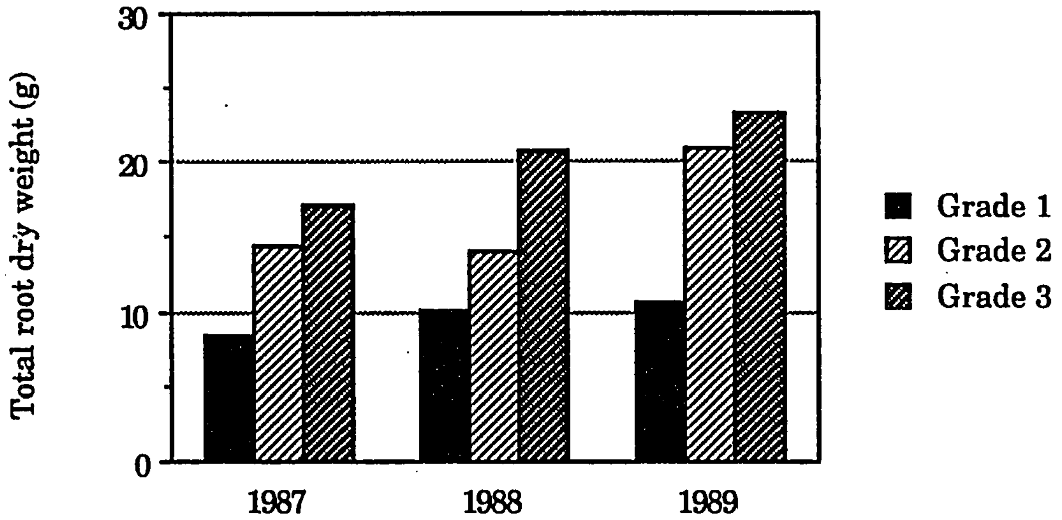


Figure 13. Average dry weights of total root systems for excavated seedlings, by root grade

$p < 0.01$), and between height and stem and shoot dry weights ($r^2 = 0.56$ to 0.68, $p < 0.01$) occurred in both 1988 and 1989. Seedling diameter was also strongly correlated with length of laterals ($p < 0.05$), and all dry weight measurements ($r^2 = 0.64$ to 0.83, $p < 0.01$) in both years. As previously indicated, total number of first-order lateral roots was correlated with original root grade, and was also strongly correlated with total numbers of second-order laterals ($r^2 = 0.62$ to 0.79, $p < 0.01$) in both years. This corroborates the hypothesis that a larger framework of first-order lateral roots at the time of outplanting can provide more sites for elaboration of higher-order lateral roots in the first few years after outplanting. Dry weights for all plant parts were significantly correlated with each other ($r^2 = 0.57$ to 0.97, $p < 0.01$) in both 1988 and 1989.

General growth patterns

Comparison of trends suggested by total shoot dry weight (Figure 9) and total root dry weight (Figure 13) indicates more shoot growth between 1987 and 1988 samplings, and more root growth between 1988 and 1989 samplings. This may have been partially due to sampling time, since seedling shoots flushed before sampling in the spring of 1988, while a significant proportion of seedling root growth is a late season phenomenon. Drought conditions in 1988 and drought combined with poor weed control in 1989 were additional factors that may have shifted seedling growth "priorities" toward the roots (as suggested by Dickson, 1991). In fact, for harvested trees, average root to shoot ratios (based on dry weights) were greater in 1989 (r:s = 2.0) than in 1988 (r:s = 1.5). Factors which damaged the seedlings may have been more detrimental to the shoots of plants than to the roots (e.g., cattle, deer, rabbits), although some damage to seedling roots systems probably also occurred (primarily gophers, but probably also other soil fauna).

Total dry weights for excavated seedlings are shown in Figure 14. Dry weights of grade 3 seedlings remained at least two times greater than those for grade 1 seedlings for all three years of analysis, and close to two times greater for grade 2 seedlings versus grade 1 in two out of the three years.

Morphology of excavated seedlings

Photographs of seedling root system morphology to summarize the characteristics of grade 1 versus grade 3 seedlings are included in Figure 15. Grade 1 seedlings have much smaller total rootmass (Figure 15a and 15c) than grade 3 seedlings (Figure 15b and 15d) in any year of the study. In addition, large first-order lateral roots are more evenly distributed along the length of the taproot for grade 3 seedlings. Casual observation of root system morphology at the time of planting and at the time of excavation suggested that the "permanent" lateral roots were for the most part still viable roots and other than callus roots were still the functioning "framework" of seedling root systems. In addition, extension of these roots was probably a major factor in production of relatively long laterals within the first field season. Numbers of callus roots produced at the lifting wound are about the same for all three seedling grades, although callus roots produced by grade 3 seedlings are larger in diameter and generally longer. For most seedlings, callus roots extended to soil depths of approximately 1 m by the end of the first growing season. The relative abundance of second- and higher-order roots on grade 3 seedlings suggests more effective soil exploitation by these seedlings (see also Lyr and Hoffman, 1967).

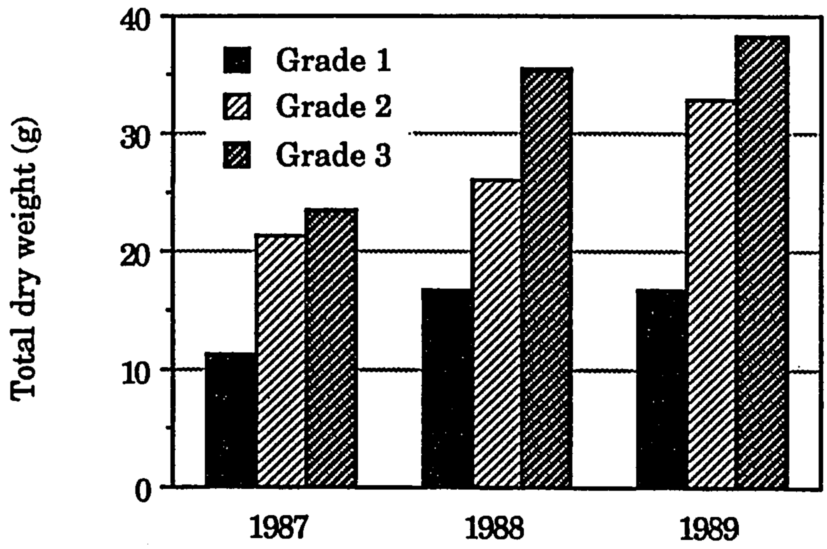
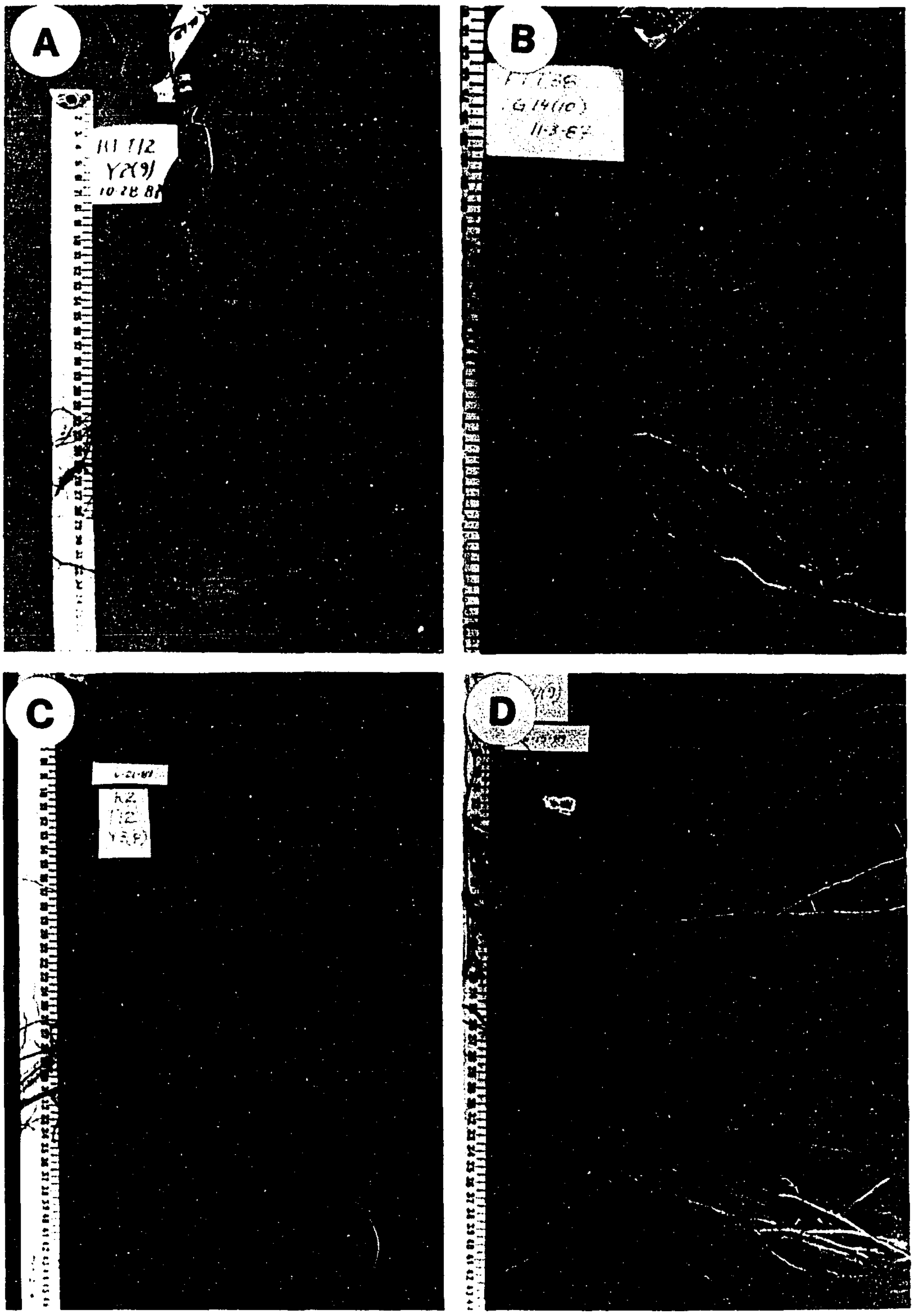


Figure 14. Average total dry weights for excavated seedlings, by root grade

Figure 15. Root system morphology of seedlings excavated in 1987 and 1989

Grade 1 seedlings had fewer roots, predominantly those which formed at the lifting wound at the base of the taproot, (A) in 1987, and (C) in 1989. Grade 3 seedlings had permanent first order laterals evenly distributed along the entire taproot, (B) in 1987, and (D) in 1989. Extensions of preexisting lateral roots allowed greater expansion of grade 3 seedling root systems.


A
B
C
D

SUMMARY AND CONCLUSIONS

1. Field survival data for the second and third year indicate a much greater probability of survival for seedlings with 5 or more permanent first-order lateral roots than for seedlings with 4 or fewer permanent first-order lateral roots.

2. Height growth based on field measurements was inadequate for all seedlings, but was significantly greater for grade 3 than for grade 1 seedlings. Initial differences in seedling diameter between root grades were significant and were greater by the end of the third year. Incremental height and diameter growth data for three years indicated most significant differences between grades 1 and 3 seedlings.

3. Based on partial correlation analyses, first-year growth was significantly and positively correlated with initial root grade ($r^2 = 0.20$, $p < 0.01$), but significantly and negatively correlated with initial height ($r^2 = -.01$, $p < 0.01$). This suggests that grading systems which include analysis of seedling root characteristics may be better predictors of seedling success (even in terms of height growth) than grading systems that emphasize initial height.

4. Measurements of harvested trees indicated statistical differences for shoot characteristics (height, diameter, and shoot dry weight) and root characteristics (length of lateral roots, width of rootmass, total first-order lateral roots, total second-order lateral roots, and root dry weights) of seedlings with 4 or fewer permanent lateral roots compared with seedlings having 10 or more permanent lateral roots. Seedlings with 5 to 9 permanent lateral roots were not statistically different from those with 10 or more, although in many

cases they were significantly different from those with 4 or fewer permanent laterals.

5. Combined results for seedling survival and growth indicate that red oak seedlings with 5 or more permanent first-order lateral roots have a greater probability of success both in terms of establishment and competitive early growth. Poor height growth of all seedlings in this study may have been partially due to drought conditions in the second and third year, but also indicates the need for adequate weed control (perhaps for as long as five years) and some degree of protection from animal damage for successful plantation establishment.

PART II. SURVIVAL AND GROWTH OF RED OAK SEEDLINGS WITH RESPECT TO SITE FACTORS

INTRODUCTION

Seedling establishment is often documented by mortality or morphology measurements early in stand development without an adequate understanding of how the seedling responds to environmental factors after outplanting (Grossnickle and Blake, 1987). The second major goal of this study was to evaluate seedling development in the context of seedling interaction with the planting site. It is widely held that site conditions, and in particular soil characteristics, can modify root growth to a great extent (e.g Kramer and Kozlowski, 1979). The "plasticity" or responsiveness of seedling root systems to the soil environment (rate of growth and extent of lateral spread of roots) is also linked to the above ground growth performance of the seedlings. Hence, a number of reforestation researchers have articulated the need to identify soil factors that are critical to overall seedling performance (for example, Sutton, 1980a; Duryea, 1985). In addition, some workers have called for "prescription" planting of "high quality" stock on certain types of sites, or more careful site selection (particularly for hardwoods) to increase plantation establishment success (Hobbs, 1984; South et al., 1985; Teclaw and Isebrands, 1991).

To include an assessment of seedling performance with respect to site factors, sites for this study were chosen to provide a variety of soil environments (different soil parent materials and physiographic positions) within an area having similar macroclimatic conditions.

LITERATURE REVIEW

Root System Plasticity

Shoot growth patterns within a species may be fairly constant across a range of sites. Roots, however, respond to a variety of stimuli in ways that are adaptive, especially in stressful environments (Feldman, 1984). Haasis (1921) and Turner (1936) were among early workers who commented on the influence of site (soil) factors on root system characteristics, noting the great flexibility of development which could result in pronounced variability within a species relative to soil features. Roots, in fact, appear to have the capacity to respond to very local environmental conditions, such that even within a single plant individual roots may grow at different times or rates depending on favorability of microenvironmental conditions (Lyr and Hoffman, 1967; Coutts and Lewis, 1983).

Sutton (1980b) indicated that flexibility of root system form is in large part due to the "plastic" nature of secondary root system elements (first- and any higher-order lateral roots and root hairs), and that plasticity increases with age of the plant. Gale and Grigal (1987) indicated that inherent differences in root distribution were more noticeable in seedlings (i.e., in a given setting after a certain time, differences between species are masked by similar responses to site factors). In addition, these workers noted that midtolerant (including species of oak) and tolerant tree species appear to be phenotypically more plastic in terms of root system characteristics than intolerant species.

Although it is often difficult to separate the effect of genetic and environmental factors on plants in general (and roots in particular), some work has demonstrated within clone differences in root system form on different plantation sites (e.g., Faulkner and Fayle, 1979). This suggests that observations of variation in root system form in studies lacking control of the genetic component are probably legitimate (although the data may be more difficult to interpret).

Given the overwhelming effect of site factors on seedling morphogenesis, evaluation of seedling performance on a wide range of sites would be necessary to validate any generally applied seedling grading criterion.

Analysis of Seedling Performance With Respect to Site Factors

A large volume of literature documents studies of tree or seedling performance in relation to site factors. Often, these studies have involved relating plant performance to some general measure of "site index" (height of dominant and codominant trees on a site at a given age, see for example, Turner, 1936, for shortleaf pine; Thomson, 1956, for black walnut in Iowa; Olson and Hooper, 1972, for red oak in North Carolina). More recent studies of seedling performance which were designed to test other (previous treatment) differences turned into evaluations of seedling survival and growth as influenced by site characteristics. For example, Ritchie and Dunlap (1980) and Sutton (1983) indicated that survival and height growth of outplanted conifer seedlings from seedling lots with different root growth potentials were affected more by outplanting site characteristics than by initial root growth potential. Hay et al. (1987) reported that outplanting site variation masked treatment differences for yellow poplar seedlings from fertilization and mycorrhizal inoculation trials. Most of the workers cited above hypothesized that specific differences in soil properties and microclimatic conditions were probably responsible for significant variation in survival and height growth on different outplanting sites (although they didn't all test their hypotheses!). The responsiveness of seedling root systems to soil conditions and documentation of varying root system morphology in response to soil factors suggests an examination of seedling root system development with respect to soil factors in particular.

Soil Factors and Seedling Root Development

A number of workers have listed soil properties which may affect root system development: structure (aggregate shape, size, strength), porosity, texture, bulk density, presence of coarse fragments, aeration, water-holding capacity (or available water), temperature, depth, thickness of A horizon, pH, nutrient availability (especially nitrogen, phosphorus, and potassium), cation exchange capacity, percent base saturation, and presence/quantity of organic matter. In general, relationships between soil factors and plant (or root) growth are usually suggested by multiple linear regression or other modelling techniques. The influence of soil physical and chemical characteristics will be reviewed separately.

Root growth and soil physical properties

Roots increase in length when cells of the root meristem divide and elongate, pushing the root tip forward. Turgor pressure in the elongating cells is the driving force for this process and must be adequate to overcome constraints imposed by the cell wall and the external medium (Taylor, 1974). Soil physical conditions affect the availability of water to supply turgor and determine the magnitude of externally imposed constraints (Mirreh and

Ketcheson, 1973; Taylor, 1974; Logsdon et al., 1987). In most soils, roots grow partly by moving through existing voids and partly by moving soil particles aside (Taylor, 1974).

Authors of early investigations of root systems of seedlings often attributed seedling differences to variation in soil texture (proportions of different particle sizes in soil materials) probably most importantly through its effect on availability of soil water (e.g. Holch, 1931; Turner, 1936). Some contemporary studies also emphasize the importance of soil texture (Kochendorfer, 1973; Stein, 1978). In undisturbed soil material, it is difficult to separate the effects of soil texture, soil structure, and available water on plant roots. Most investigations of the effect of soil structure per se have focused on root impedance (resistance to elongation) due to "strength" of natural structural units in soil, and the natural tendency for roots to follow pores (interped spaces or channels) wherever possible (Fehrenbacher and Snider, 1954; Stolzy and Barley, 1968; Champion and Barley, 1969; Cockroft and Tisdall, 1974; Taylor, 1974; Dexter, 1987; Logsdon et al., 1987). Soil bulk density is another parameter often measured to indicate the degree of soil resistance to root penetration. Some research has indicated variation in root morphology with respect to soil bulk density: Stein (1978) reported that roots were generally longer at lower soil bulk densities, and Ponder (1979) reported more growth and proliferation (and higher dry weights) for roots grown at lower soil bulk densities. A great number of workers have noted that roots are unable to penetrate high density soil materials with little pore space (e.g. Fehrenbacher et al., 1965). Taylor (1974) indicated, however, that if other factors were more limiting (e.g. available water), soil strength probably has little effect on root growth.

Studies of soil aeration effects are less common than studies of other soil physical characteristics, and effects of aeration levels in undisturbed soil materials are difficult to separate from effects of mechanical impedance, water content, and bulk density, since all of these are related to the presence of aggregates and air- or water-filled spaces between them (Warnaars and Eavis, 1972).

A synthesis of the combined effects of soil strength and soil water potential on root growth is given by Dexter (1987). As earlier mentioned, water potentials (and the balance between internal water potential of the plant and external water potential of the soil) are critical for root growth (Dexter, 1987). Many models of soil productivity for forest or potential forest sites include a component describing water holding capacity or available water capacity of the soil (e.g., Fralish and Loucks, 1975; Gale and Grigal, 1986). Dwyer et al. (1988) reported that root depth and distribution were most strongly influenced by available water for corn, soybeans, and barley. Water relation patterns of transplanted tree seedlings are especially critical to seedling establishment (Grossnickle and Blake, 1987). Larson and Whitmore (1970) and Larson (1980) specifically studied the effects of moisture stress on red oak seedlings. Their results showed that root regeneration and most aspects of seedling shoot growth decreased as soil moisture stress increased.

A few studies have explored the relationship between soil temperature and root growth for northern hardwoods (e.g., Larson, 1970). Generally, minimum temperature requirements for root growth are lower than those for shoot growth, although the identification of the optimal temperature for root growth is often confounded by episodic growth patterns in tree seedlings. Periods of maximum root extension (which generally coincide with cooler soil temperatures in early spring and late fall) are probably more strongly affected by source-sink relations within the plant than by soil temperature.

Some workers have noted significant variation in seedling growth related to soil depth or "effective rooting depth" (Hay et al., 1987). This factor most often comes into play where soils are shallow to some impervious barrier such as a soil pan or bedrock (Fehrenbacher et al., 1965; Yen et al., 1978; Gale and Grigal, 1986).

Thickness of A horizon material is a physical characteristic of undisturbed soil material that often has a measureable effect on plant root growth (Gale and Grigal, 1986; Hay et al., 1987). However, the salient features of most A horizons that affect root growth are probably soil chemical properties such as nutrient and organic matter levels, addressed in the subsequent discussion of soil chemical properties.

Root growth and soil chemical properties

It has long been recognized that "fertile" soil promotes proliferation of roots, especially lateral roots. Characterization of soil chemical properties has most frequently involved analyses of pH, macronutrients, cation exchange capacity, base saturation, and organic matter content. Many of these factors (or their derivatives) are also included in models used to predict site suitability or productivity for particular species (e.g., Gale and Grigal, 1986). Probably the most dramatic evidence for the influence of soil chemical factors on root system form come from "gradient" studies, where different portions of the same root system respond differentially to varying levels of nutrients or organic matter (as reported by Coutts and Lewis, 1983; Davis et al., 1983). Black (1968) indicated that root proliferation in "enriched" media is usually restricted to second- and higher-order roots. Some workers have reported greater lateral spread of first-order roots and fewer higher-order roots in "nutrient poor" and coarse textured soils compared with more fertile and generally finer-textured soils (Lyr and Hoffman, 1967). Black (1968) suggested that this root morphology might be related to levels of hormones produced in the root tip in response to low nutrient levels.

Other Site Factors

Site physiography (elevation, aspect, percent slope, surface drainage, degree of exposure) and attendant microclimatic conditions are also important to seedling establishment and growth. Some studies of oak regeneration and growth in particular have focused on topographic features: Lunt (1939) reported greater height growth on lower slope reaches than on higher positions, and Eschner (1952) indicated significant effects of aspect on oak stands. Both workers indicated that effects of slope position and aspect were probably important indirectly through their influence on water relations. Whether important directly or indirectly, slope percent and aspect are factors which are often included in soil productivity models such as the one described by Gale and Grigal (1986).

MATERIALS AND METHODS

General Information

As a part of this study of red oak seedling root morphology and the influence of site characteristics on seedling development, field and harvest data collected as described in Part I are used for this analysis of site factors.

Soil Characterization

Soil profiles were described by digging one pit approximately 1 m deep by 2.5-3 m wide (at the top) on each of eight plots. Soil descriptions were made using standard terminology (Soil Survey Staff, U.S.D.A., 1981) and are included in Appendix B. Bulk samples were taken from each soil horizon for laboratory analyses. Undisturbed clods or core samples were also taken for determination of soil bulk density.

Laboratory characterization of soil was done on samples of each horizon that were air-dried and passed through a 2-mm sieve. Particle size distribution was determined by the hydrometer method detailed by Sandor (unpublished class notes) after pretreatment with hydrodgen peroxide to remove organic matter (modified from Walter et al., 1978). Soil pH was measured on 10 g of soil in 1:1 soil-distilled water mixtures (Peech, 1965) using a Fischer Accumet Model 420 digital pH meter. The electrode was placed at the soil-water interface. Results reported for pH are the average of two determinations. Percent total carbon and nitrogen were determined by combustion of a small sample in a LECO C-H-N 600 Analyzer. Available phosphorus (using Bray number 1 extractant, Olsen and Dean, 1965) and potassium (by ammonium acetate extraction and flame photometer measurement, Pratt, 1965) were determined at the Iowa State University Soil

Testing Laboratory. Bulk density determinations were done using either an undisturbed core or clod sample. Core samples of known volume were dried at 100 degrees C and weighed (Blake, 1965). Measurement of bulk density for field-moist clod samples (200-400 g clods) coated with paraffin were made according to Blake (1965) and corrected to dry weight after oven drying a subsample of each clod.

Data were analyzed using the Statistical Analysis System (SAS Institute, 1985).

RESULTS AND DISCUSSION

General Descriptions of Sites and Soils

The plot at the Hinds farm (H) was located in a relatively level position in the floodplain of the Skunk River, approximately 100 m from the present river channel. The soil was formed in alluvium and was loam textured at the surface with a sandy loam subsoil. The three plots at the Fick observatory represent a north-facing slope sequence from an upland position (F1) to a sideslope position (F2) and a small depression (F3). The soil sampled on plot F1 was loam textured at the surface, underlain by clay loam and sandy clay loam subsoil materials. This soil formed in glacial till. The F2 soil was similarly loam and clay loam textured, and also formed in glacial till. The soil sampled on plot F3 was loam and clay loam textured as well, and formed in local colluvium. Plots at the Rhodes farm also represent a slope sequence, from a plot on the level floodplain/terrace associated with Clear Creek (R1), to two plots located on the upland (R4 and R5), with one plot at the base of the slope (R2) and one plot on the sideslope (R3). The soil sampled on plot R1 formed in local alluvium and had a silt loam textured surface horizon, underlain by loam, sandy loam, and sandy clay loam layers. Plot R2 soil formed in local colluvium (mostly from loess) over a paleosol in pre-Illinoian till at the base of an east-facing 26% slope. Soil texture for the surface horizons was loam over clay loam subsurface materials. The soil sampled on plot R3 was characterized by sandy loam and loam surface materials and sandy clay loam subsurface textures. This soil formed on the slope (approximately 26%) in loess over a paleosol in pre-Illinoian till. The soil sampled at the summit position (R4) was also formed in loess over the paleosol. This soil was also characterized by loam surface textures and clay loam and clay subsurface textures on about a 1-2% slope. Only small core samples were taken of the soil at plot R5, to verify that it was similar to the soil at plot R4. Legal descriptions for plot locations and more detailed soil descriptions are given in Appendix B.

Field Measurements

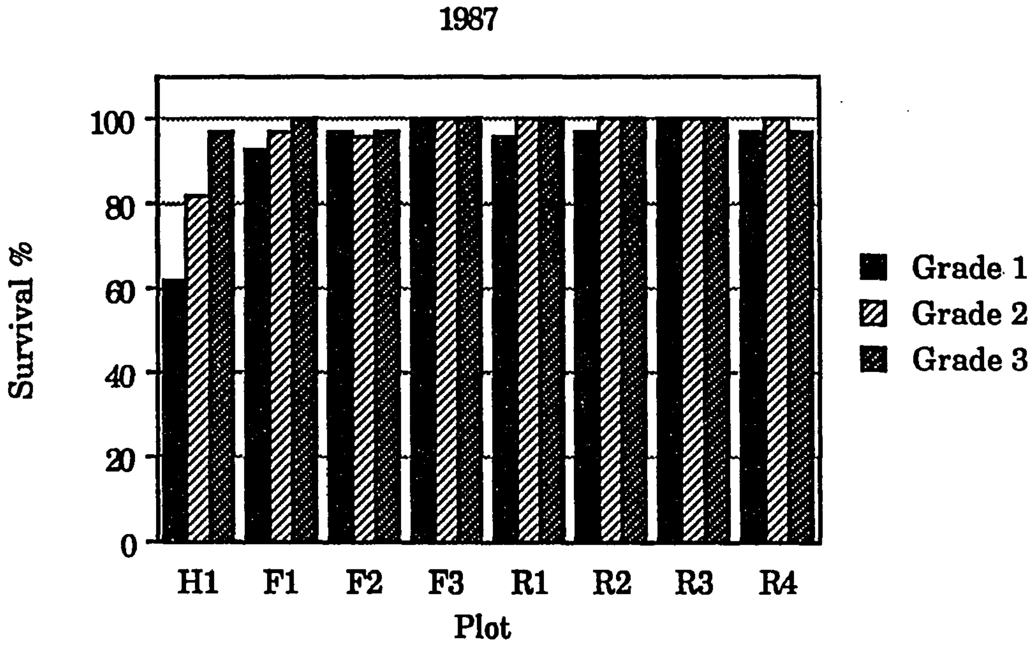
Seedling survival with respect to site

Overall means for survival on each plot (including all root grade groups) are given by year in Table 5. Results of survival counts for seedlings by root grade and by site for each year are presented in Figures 16 and 17. Site differences between H1 and all other plots are significant ($p < 0.01$) at the end of first year in field (Figure 16 and Table 5). This is primarily due to poor performance of grade 1 seedlings at Hinds (just over 60% survival). In 1988 mortality of grade 1 seedlings was greater on all sites than in 1987 (Figure 16) but for overall means the only significant differences again are between plot H1 and the rest. In 1989, plots H1 and R4 had significantly lower survival than all others, and survival on plot F1 was significantly lower than all others except R3. There were no significant differences in survival at the end of three years between plots F2, F3, R1, R2, and R3 (Table 5 and Figure 17). These plots were in physiographic positions that may have received moisture from run-on in addition to incident precipitation (especially compared with F1 and R4), and had soil characteristics (higher clay contents and low chroma colors in lower B horizons) which indicated the likelihood of higher subsoil moisture levels (especially compared with H1): both of these factors would have been important in the drought of 1988 and 1989. In 1988 and 1989, standard

Table 5. Summary of survival rates (percentage) of red oak seedlings on eight sites for three years after outplanting

					Site				
Year	H	F1	F2	F3	R1	R2	R3	R4	LSD[a]
1987	80	97	97	100	99	99	100	98	9.0
1988	56	85	88	94	96	99	96	90	15.1
1989	28	60	81	90	80	85	78	28	12.1

[a]LSD (least significant difference, $p < 0.01$) calculated using the Type III MSE for plot*root grade.



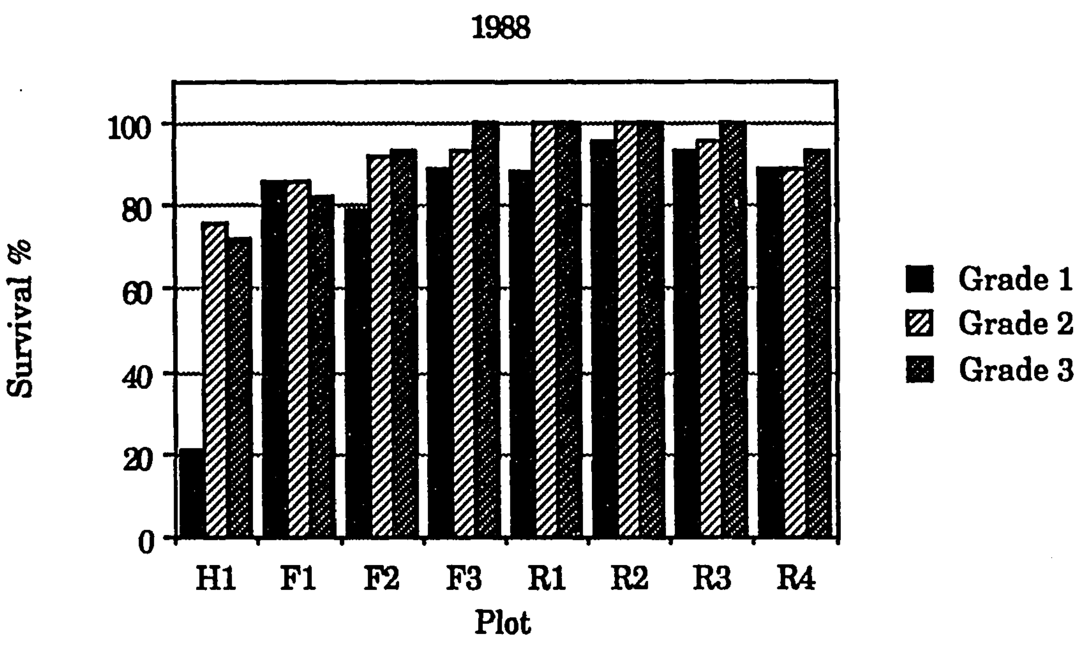


Figure 16. Percentage survival in 1987 and 1988, by plot and by root grade

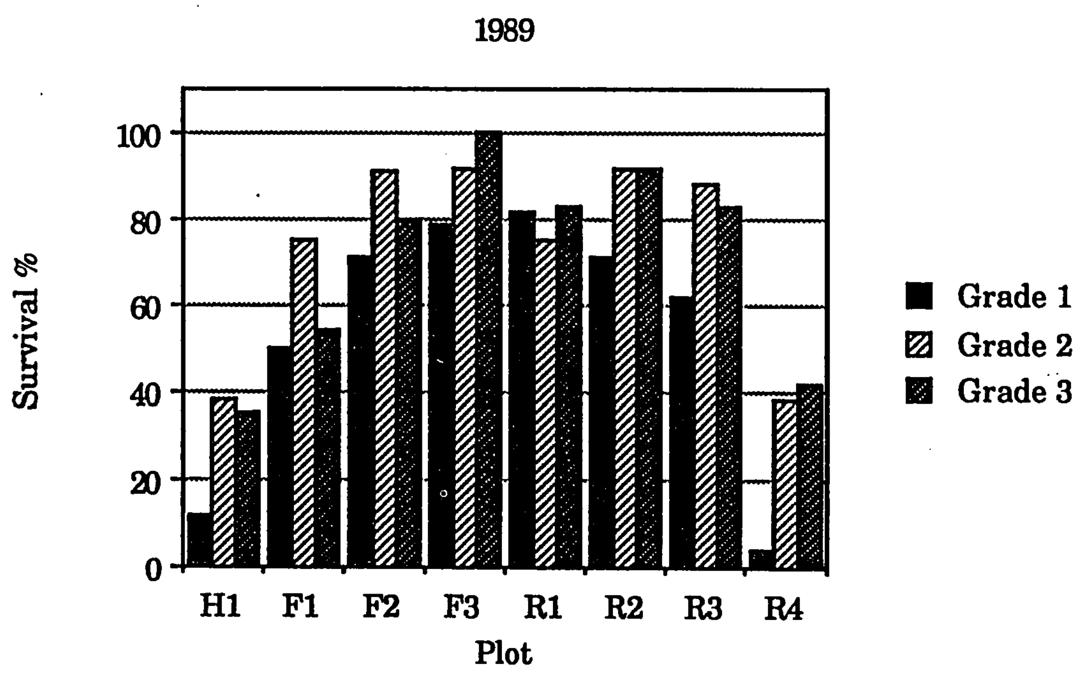


Figure 17. Percentage survival in 1989, by plot and by root grade

deviation from the mean within a root grade across sites was lowest for grade 2 seedlings, compared with standard deviations from the mean for grade 1 or grade 3 seedlings. Based on information from harvested trees, grade 2 seedlings had higher root:shoot ratios than either grade 1 or grade 3 seedlings, which may have been advantageous on the harshest sites. It appears that survival of seedlings with either very small root systems or very large root systems (and attendant shoot characteristics) was more influenced by site factors (and possibly climatological factors) than those of intermediate size (Figure 17). Economically, it may be advisable to "prescription plant" very specific kinds of stock on particularly stressful sites (in terms of exposure, lack of moisture, and degree of competition), e.g., avoid planting small stock with few roots or stock with relatively small root:shoot ratios regardless of numbers of seedling roots on those sites.

<u>Seedling growth with respect to site</u>

Mean values for height and diameter characteristics of seedlings on the different sites at the time of outplanting (initial) and at the end of the first, second, and third years after planting are shown in Figure 18 and summarized in Table 6. Initial height is included in Table 6 to demonstrate that there were no significant differences between plots for seedling height at the time of planting. There were, however, significant differences ($p < 0.01$, in spite of randomization) between plots for initial diameter: seedlings planted on plots H1, F2, and F3 were initially significantly smaller in diameter than seedlings planted on plots R1, R2, and R3.

<u>Height growth</u> At the end of the first year in the field, there were already significant differences in average seedling heights between plots

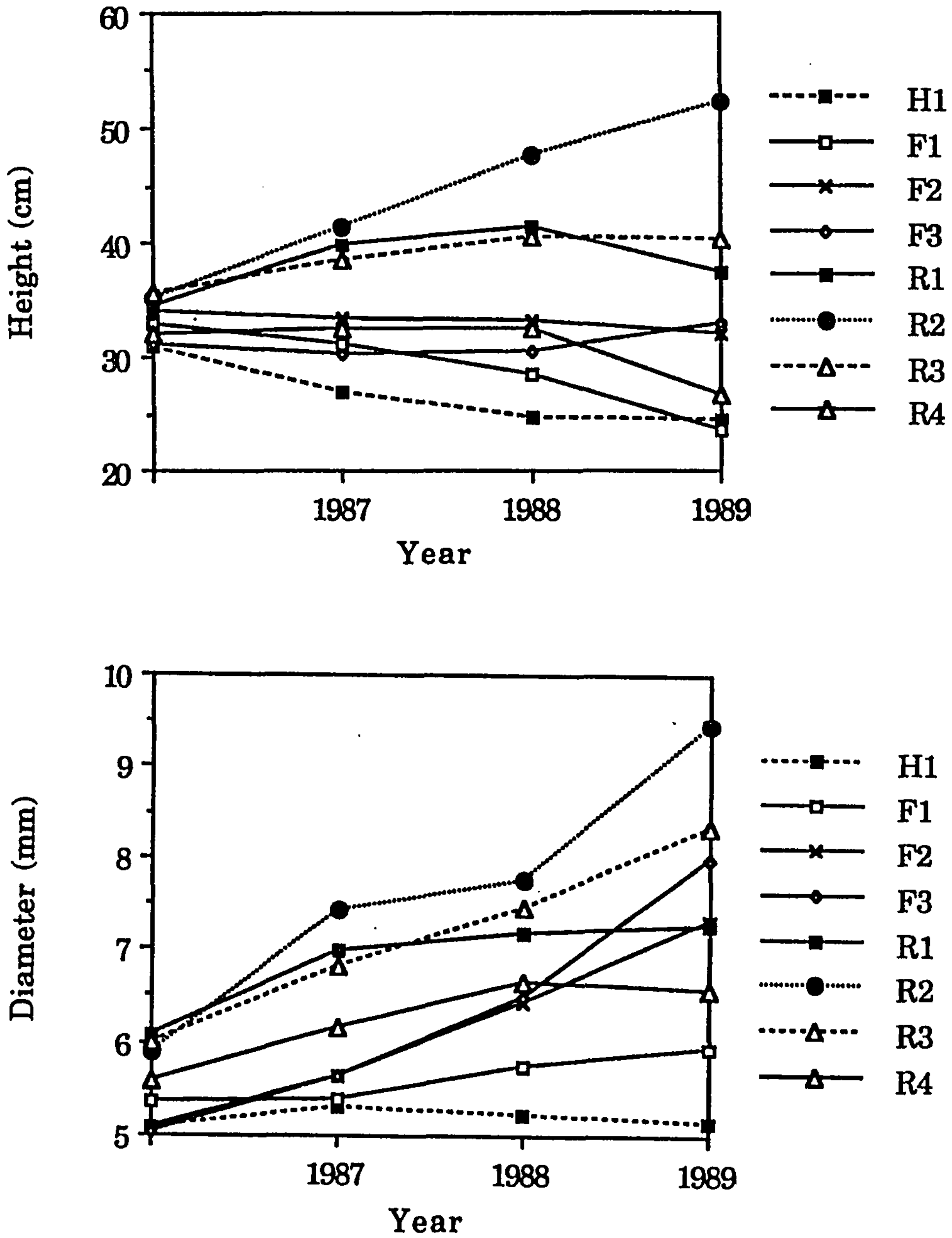


Figure 18. Average height and diameter for all seedlings for three years, by plot

Table 6. Means for seedling height (cm) and diameter (mm) by site for three years after outplanting

	Site								
Year	H	F1	F2	F3	R1	R2	R3	R4	LSD[a]
					Height				
Initial	30.4	33.7	32.9	31.7	34.9	35.7	34.6	32.0	7.4
1987	22.0a[b]	31.8b	33.1bc	30.8ab	40.3c	42.5c	39.2bc	35.2bc	8.6
1988	20.9a	30.2b	33.0b	29.9ab	42.7c	49.7c	42.6c	36.7bc	9.0
1989	24.5a	23.6a	32.0ab	33.0b	37.8b	52.2d	40.2bc	26.8a	8.6
					Diameter				
Initial	4.99a	5.46a	5.12a	5.16a	6.32b	6.12b	6.09ab	6.04ab	0.84
1987	4.25a	5.45b	5.64b	5.65b	7.19c	7.62c	6.94c	6.79c	0.99
1988	4.64a	5.93ab	6.44bc	6.50bc	7.30cd	8.07d	7.78cd	7.51cd	1.33
1989	5.13a	5.93ab	7.31cd	7.98d	7.33cd	9.44e	8.32de	6.57bc	1.33

[a]Least significant difference ($p < 0.01$) calculated using the Type III MSE for plot*root grade.
[b]Numbers followed by the same letter within a row are not statistically different ($p < 0.01$).

(Figure 18 and Table 6). H1 seedlings were significantly shorter than all other plots except F3 ($p < 0.01$). F1 and F3 seedlings were significantly smaller than R1 and R2 seedlings. F3 seedlings were also significantly shorter than R3 seedlings. Relationships between plots at the end of the second year were similar to first-year results. Plots R1, R2, and R3 were the only sites where appreciable height growth was evident during the second year. Negative growth (dieback, or death of taller stems) was characteristic of H1 and F1 seedlings during the second year, while F2, F3, and R4 seedlings were on the average unchanged. It may have been that initial effects of the 1988 drought were more pronounced on more exposed (F1, R4), coarser textured (H1), or generally more well drained (F1, F2) sites. By the end of 1989, seedlings on plot R2 were significantly larger on the average than those on all other plots, and seedlings on plot R3 were significantly larger than all others except those on plots R2 and R1. Only seedlings on plots R2 and F3 showed evidence of a positive average growth trend for the 1989 growing season, and only seedlings on plots R2, R3, R1, and F3 (in descending order of amount of growth) had cumulative height growth for the three years. Again, these plots were in positions which may have afforded more available soil moisture to the seedlings as well as less exposure to wind, which may have been critical in drought years.

Diameter growth At the end of the first year in the field, seedlings on plots R1, R2, and R3 had significantly larger diameters on the average than those on plots H1, F1, F2, or F3 (Figure 18 and Table 6). Seedlings on plot R4 had significantly larger diameters than those on plot H1 ($p < 0.01$), but significantly smaller diameters than seedlings on plot R2 ($p < 0.05$). On the average, there was little diameter growth on any plot during the 1988 field season. In 1989, average diameter increments were largest for seedlings on plots F3, R2, F2, and R3 (in descending order). At the end of the third year, seedlings on plots H1 had significantly smaller average diameters ($p < 0.01$) than those on plots R2, R3, F3, F2, and R1. Again, these relationships may be partially explained by degree of exposure of the site, and relative amounts of subsoil moisture. Differences between seedlings on plot R4 and those on plots R2 and R3 were also significant. Although there were significant differences in seedling diameters between plots at the time of planting (which occurred randomly), seedlings other than those on plot H1 "outgrew" those differences within the three years of the study.

Correlations between seedling growth and selected soil properties

The CORR procedure of SAS was used to generate a partial correlation matrix to analyze relationships between height and diameter growth and specific soil properties. Mean values for seedling characteristics presented in Table 6 and weighted means for surface soil (A horizons) and subsurface soil (B horizons) values for pH, total carbon, total nitrogen, available phosphorus, available potassium, bulk density, and percent sand, silt, and clay were used for this procedure. Results for all laboratory determinations on soil and a list of the weighted means used for this analysis are given in Appendix C. Selected results of the CORR procedure are summarized in Table 7. Significant negative correlations between surface and subsurface soil pH and first- and second-year height and diameter were calculated. Surface horizon levels of available P were significantly and negatively correlated with second-year diameter and third-year height and diameter. Surface horizon levels of

Table 7. Correlation coefficients and probabilities of larger correlation coefficients for seedling means from Table 6 and weighted means for selected soil properties

	Seedling characteristics					
Soil parameters	First-year height	First-year diameter	Second-year height	Second-year diameter	Third-year height	Third-year diameter
Srf[a] pH	-0.70[b]	-0.55	-0.62	-0.64	-0.39	-0.48
	0.054[c]	0.161	0.103	0.088	0.342	0.224
Sb pH	-0.80	-0.77	-0.76	-0.73	-0.54	-0.49
	0.016	0.026	0.028	0.040	0.166	0.216
Srf P	-0.49	-0.58	-0.58	-0.74	-0.63	-0.73
	0.214	0.130	0.136	0.037	0.097	0.040
Srf K	-0.56	-0.61	-0.62	-0.53	-0.70	-0.51
	0.146	0.109	0.104	0.178	0.051	0.196
Sb SA[d]	-0.11	-0.09	-0.11	-0.15	0.05	-0.00
	0.790	0.823	0.801	0.726	0.902	0.999
Srf CL	-0.56	-0.45	-0.50	-0.45	-0.36	-0.34
	0.152	0.259	0.202	0.267	0.384	0.415
Sb CL	0.44	0.43	0.37	0.40	0.07	0.06
	0.275	0.286	0.362	0.329	0.867	0.890

[a]Srf refers to surface (A) horizon values, Sb refers to subsurface (B) horizon values.

[b]Pearson correlation coefficient.

[c]Probability of a greater value of the coefficient.

[d]SA = sand, CL = clay.

available K and third year height were significantly and negatively correlated. In and of themselves, these correlations are difficult to explain. Generally speaking, the fastest growing trees were on plots for which the lowest soil pH values were measured, and levels of available P and K are essentially covariates of the soil pH (their solubility and availability are determined to some extent by soil pH). The expected negative relationship between height and diameter growth and subsurface sand contents (higher on excessively drained sites) was evident , but correlations calculated were not significant. Generally, A horizon clay contents were negatively related to seedling height and diameter, although B horizon clay contents were positively correlated with seedling growth (again, these relationships were not statistically significant). The general lack of significant relationships between soil properties and seedling height and diameter growth may have been partially due the overwhelming effect of climatological factors (extreme drought conditions) and to the small sample size used in the correlation analysis (n=8, since the analysis was based on plot means).

Measurements of Harvested Trees

Mean values for characteristics measured on trees excavated in 1987, 1988, and 1989 for each plot are given in Table 8. For comparison of root grade groups in Part I, means for height and diameter of excavated trees (n = 16 or 12) did not deviate significantly from means for those characteristics for all trees measured in the field. However, when stratified by plot (n = 6), and especially when stratified by grade within plot (n = 2), means for excavated trees did deviate from those for all trees on a plot or within a grade on a plot. The biggest discrepancies in seedling height and diameter means occurred in

Table 8. Means by plot for three years for characteristics measured on excavated trees

	Plot								
Characteristic	H1	F1	F2	F3	R1	R2	R3	R4	LSD[a]
					1987				
Orig. root grade	5.0	7.0	9.3	6.2	6.7	7.2	7.3	6.3	4.5
Height	33.6a[b]	44.8ab	43.6ab	36.5ab	47.3ab	53.4b	45.8ab	36.6ab	17.6
Diameter	7.8	7.7	7.3	7.8	7.8	8.9	8.7	6.7	2.8
Longest lateral	31.8	46.3	52.3	42.4	48.2	49.4	54.2	34.8	35.9
Width roots	40.0	44.5	37.5	30.2	39.5	58.2	40.2	37.8	32.0
New root grade	6.0a	9.0ab	11.5ab	7.0a	14.5b	10.8ab	11.3ab	9.0ab	6.0
Tot. 1st laterals	16.3a	23.3ab	24.0ab	21.3a	40.2b	28.5ab	21.7a	27.7ab	17.3
Callus roots	3.4	2.0	3.8	2.2	2.5	3.8	5.3	2.2	4.3
Tot. 2nd laterals	115	139	192	109	248	186	187	124	159
Dry wt. stem	2.0a	5.1abc	4.5abc	2.5ab	7.2bc	7.3bc	7.9c	3.5abc	5.1
Dry wt. tap	4.5a	7.4ab	8.8abc	5.4a	14.1bc	13.1bc	15.0c	8.6ab	6.4
Dry wt. lats	x	2.0	2.3	1.7	5.4	4.0	4.0	2.1	4.2
Dry wt. shoot	2.0a	5.1abc	4.5abc	2.5ab	7.2bc	7.3bc	7.9 c	3.5abc	5.1
Dry wt. roots	4.5a	9.4abc	11.2abcd	7.0ab	19.6d	17.0cd	19.1cd	10.7abcd	9.9

[a]Least significant difference between two means ($p < 0.01$) calculated using the Type III MSE for plot*root grade.
[b]Numbers within a row followed by the same letter are not statistically different ($p < 0.01$).

Table 8. (Continued)

					Plot				
Characteristic	H1	F1	F2	F3	R1	R2	R3	R4	LSD
				1988					
Orig. root grade	8.3	6.5	7.7	7.3	7.0	8.2	x	x	2.7
Height	32.3	37.6	49.1	41.3	52.7	50.8	x	x	21.4
Crown depth	20.6	19.5	20.4	20.3	20.3	20.1	x	x	12.5
Diameter	7.2	7.7	7.5	7.4	8.1	8.6	x	x	2.3
Longest lateral	50.6	36.8	44.4	47.2	48.7	43.8	x	x	29.7
Width roots	31.0	34.2	34.7	42.5	37.0	50.0	x	x	26.4
New root grade	11.3	8.2	9.7	12.0	11.0	14.3	x	x	7.6
Tot. 1st laterals	26.3	18.3	17.7	27.3	25.7	27	x	x	12.9
Callus roots	3.0	3.2	4.0	3.0	3.8	4.3	x	x	2.9
Tot. 2nd laterals	402b	210ab	279ab	256ab	232ab	155a	x	x	233
Dry wt. leaves	2.7	2.5	3.7	4.9	5.1	7.0	x	x	3.8
Dry wt. stem	4.3	4.6	8.1	6.9	8.5	8.6	x	x	6.3
Dry wt. tap	8.5	9.0	10.8	11.8	11.4	15.8	x	x	8.8
Dry wt. lats	2.6	1.5	5.6	4.8	3.9	4.3	x	x	6.0
Dry wt. shoot	7.0	7.2	11.8	11.8	13.6	15.6	x	x	9.9
Dry weight roots	11.1	10.6	16.4	16.6	15.3	20.1	x	x	13.3

Table 8. (Continued)

Characteristic	H1	F1	F2	F3	Plot R1	R2	R3	R4	LSD
					1989				
Orig. root grade	8.8	6.8	7.5	6.2	5.8	7.2	6.7	6.5	4.4
Height	29.0a	39.0ab	36.3ab	41.8ab	40.8ab	71.2b	42.2ab	34.2a	34.8
Crown depth	9.9	13.0	16.3	20.7	13.7	36.2	15.5	10.8	20.3
Diameter	5.7a	7.2a	7.4a	7.6a	8.2ab	10.8b	7.0a	6.3a	2.6
Longest lateral	43.4ab	34.4ab	46.3ab	53.5ab	51.5ab	59.7b	42.7ab	32.6a	25.5
Width roots	37.0ab	42.7ab	48.7abc	46.2ab	53.5abc	82.0c	62.8ab	35.3a	33.5
New root grade	11.8	10.2	13.0	9.3	11.0	15.3	10.0	8.3	9.9
Tot. 1st laterals	23.3	24.7	27.7	21.3	32.5	22.7	19.5	30.8	21.5
Callus roots	3.7	4.5	4.7	3.8	3.2	5.3	3.7	2.3	3.5
Tot. 2nd laterals	172ab	219ab	474b	207ab	297ab	257ab	113a	180ab	351
Dry wt. leaves	0.8	1.6	2.6	2.6	2.1	10.0	3.5	1.7	3.7
Dry wt. stem	3.5a	6.2a	6.5a	8.7ab	6.5a	21.5b	5.8a	4.1a	13.7
Dry wt. tap	7.6a	10.2a	12.9a	16.7ab	12.8a	26.1b	8.8a	6.6a	12.9
Dry wt. lats	3.1	3.1	8.2	9.0	6.7	10.1	2.2	2.1	8.8
Dry wt. shoot	4.3a	7.8a	9.1a	11.4a	8.7a	31.5b	9.2a	5.9a	16.6
Dry wt. roots	10.7a	13.3a	21.2ab	25.7ab	19.4ab	36.3b	11.0a	8.7a	20.7

1987 and 1989. Since height and diameter were the only characteristics measured on all trees, significant deviations with respect to these parameters suggest that other characteristics of harvested trees might also be somewhat less representative of the whole, and should probably be considered only in a general sense. Significant differences ($p < 0.01$) between means for seedlings excavated from different plots occurred for the following parameters: height (1987, 1989), diameter (1987, 1989), length of longest lateral (1989), width of root mass (1989), new root grade (1987), total first-order laterals (1987), total second-order laterals (1988), stem dry weight (1989), taproot dry weight (1987, 1989), shoot dry weight (1987, 1989), and root dry weight (1987).

Shoot characteristics

Results for average seedling height and diameter measurements on excavated trees in 1987, 1988, and 1989 are shown for each site in Figures 19, 20, and 21. Significant differences ($p < 0.05$) for average height in 1987 occurred between seedlings excavated from plot R2 and seedlings from plots H1, F3, and R4 (Table 8). These differences reflect the general pattern shown for field measurements (Figure 18), and thus are probably not due to subsampling effects. Although there was significant variation between root grades on different plots for seedling diameter of trees excavated in 1987, significant differences ($p < 0.05$) among average values for each plot occurred only between plot R4 and plots R2 and R3. The pattern for diameter among trees excavated in 1987 is somewhat different from the pattern for all trees (by plot) in 1987 that was shown in Figure 18.

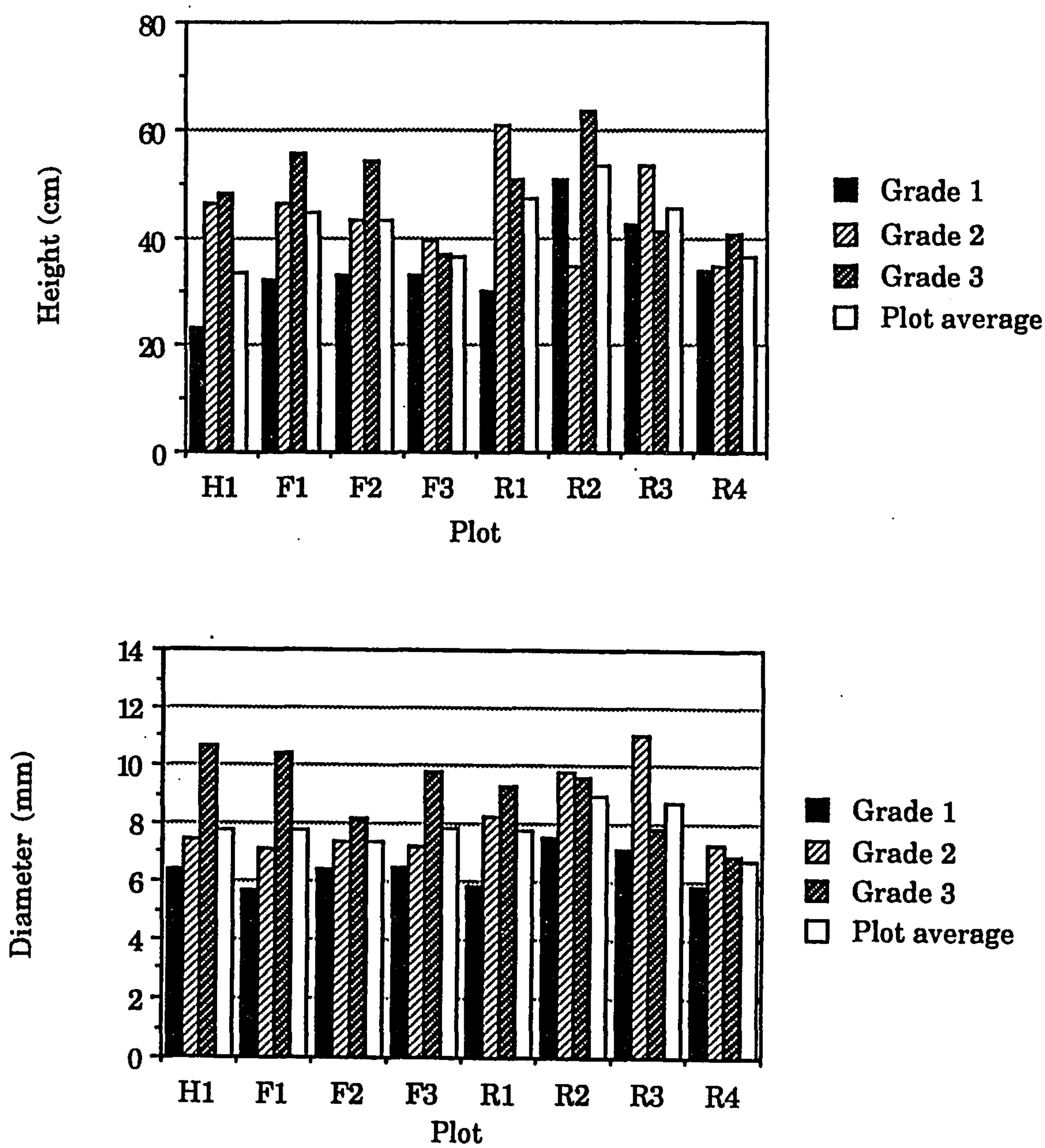
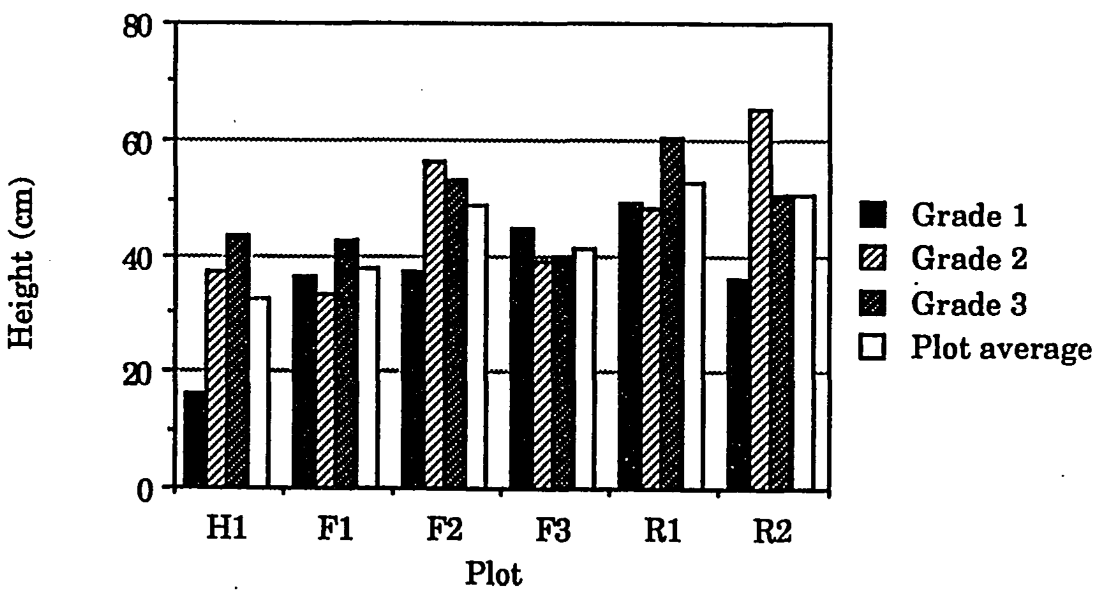


Figure 19. Average height and diameter for seedlings excavated in 1987, by plot and by root grade



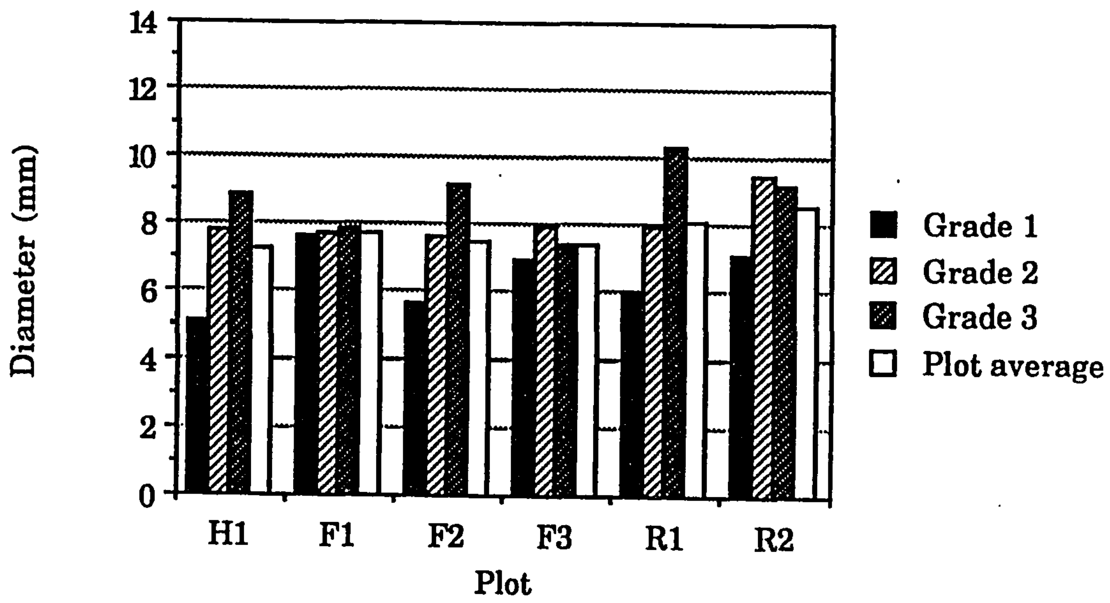
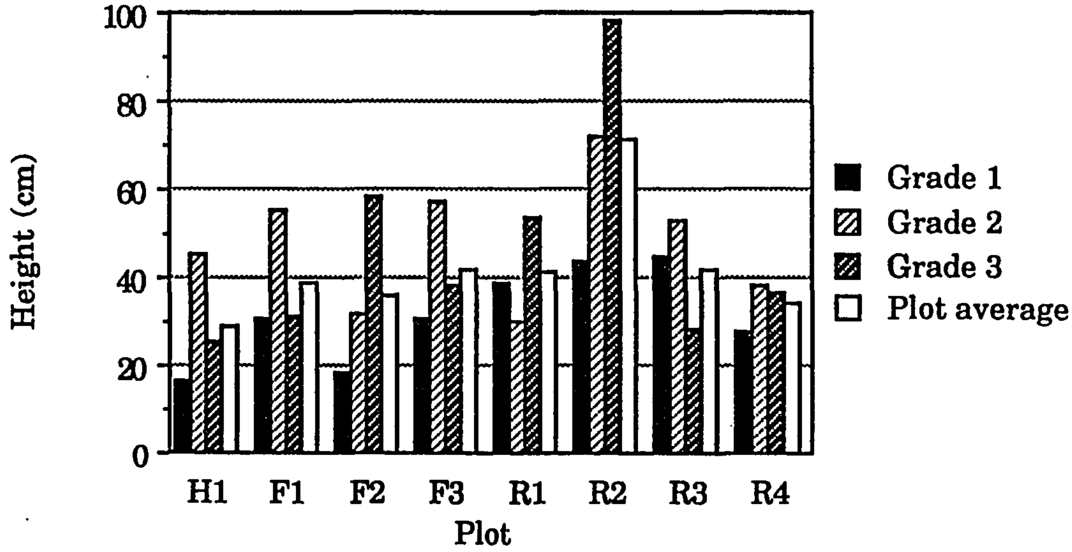


Figure 20. Average height and diameter for seedlings excavated in 1988, by plot and by root grade



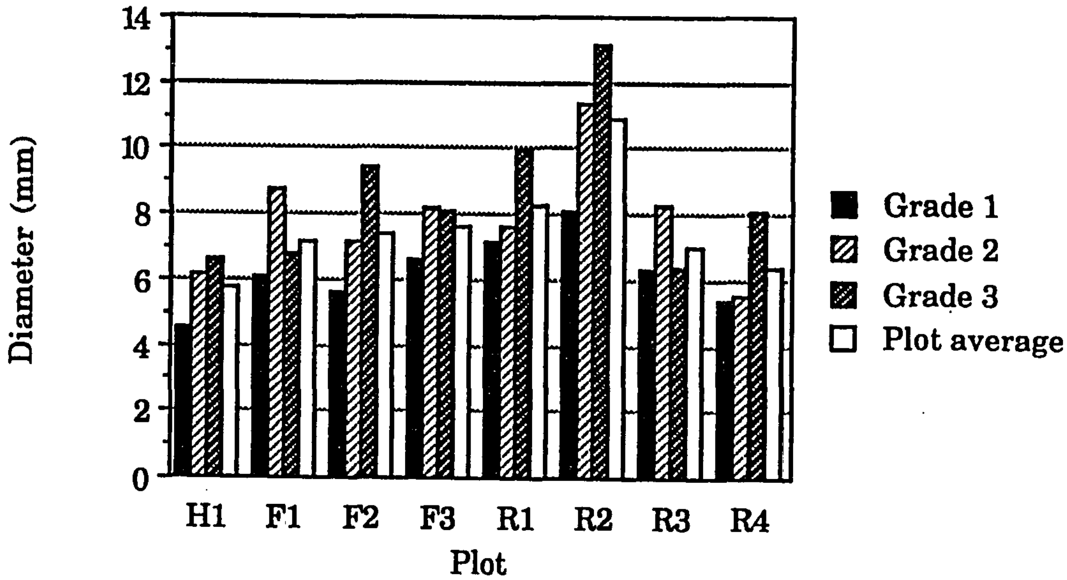
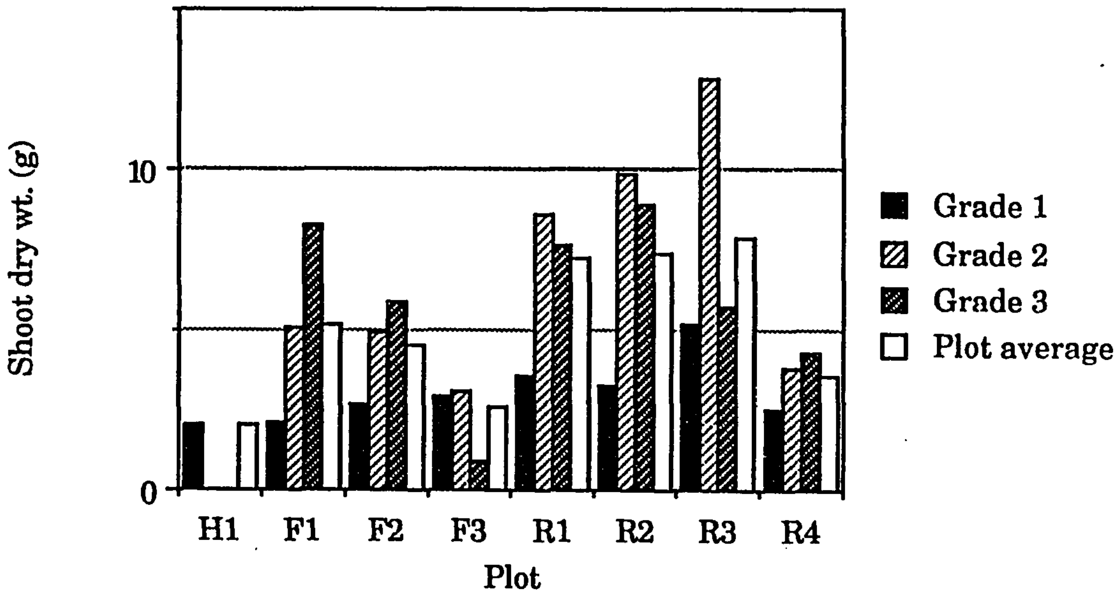


Figure 21. Average height and diameter for seedlings excavated in 1989, by plot and by root grade

In 1988, differences in average height for excavated seedlings between plot H1 and plots F2, R1 and R2 were significant ($p < 0.05$) (Figure 20). No seedlings were excavated from plots R3 and R4 in 1988. Again, these height relationships are similar to those reported for the entire set of trees measured in 1988 (Figure 18). There were no significant differences in average diameter of seedlings excavated from the six plots sampled in 1988.

Significant height differences occurred between seedlings excavated on plots H1, F1, F2, and R4 versus plot R2 ($p < 0.01$) and plots F3, R1, and R3 versus plot R2 ($p < 0.05$) in 1989 (Figure 21). For excavated seedlings, mean height of grade 2 seedlings exceeds that of grade 3 seedlings on plots H1, F1, F3, R3, and R4, and overall mean height of grade 2 seedlings is greater than grade 3 (refer to Figure 6). Plots on which grade 2 seedlings outperformed grade 3 seedlings (for all trees) were sites with the harshest conditions in terms of exposure and lack of moisture during the ongoing drought. On plot R3 in particular, mean height for grade 1 seedlings exceeds that of grade 3 seedlings. However, this trend does not appear to be similar to that for all trees based on field measurements (see Figure 5). Trends for diameter (Figure 21) for seedlings harvested in 1989 from the different plots are similar to those reported for all seedlings in 1989 (compare 1989 data in Table 6 and Table 8). Seedlings excavated from plot R2 had significantly larger diameters than all other seedlings except those excavated from plot R1.

Average dry weight data for shoots of trees excavated in 1987, 1988, and 1989 is given in Table 8 and illustrated in Figures 22 and 23. Comparison of plot H1 to the others in 1987 was not possible due to missing values. However, significant differences between plot averages for shoot dry weight occurred



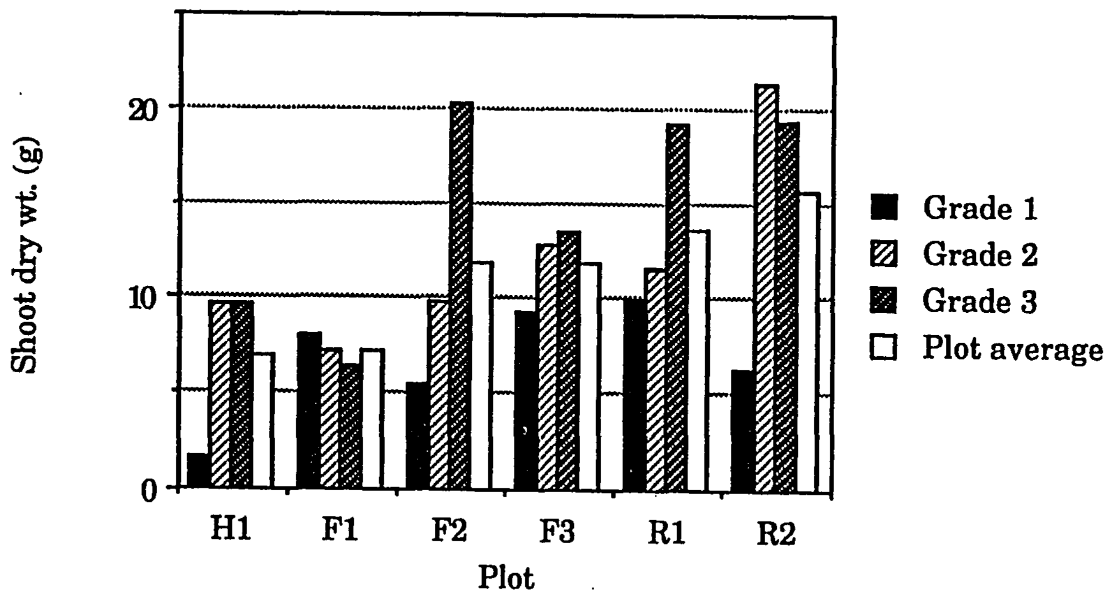


Figure 22. Average dry weights of shoots for seedlings excavated in 1987 and 1988, by plot and by root grade

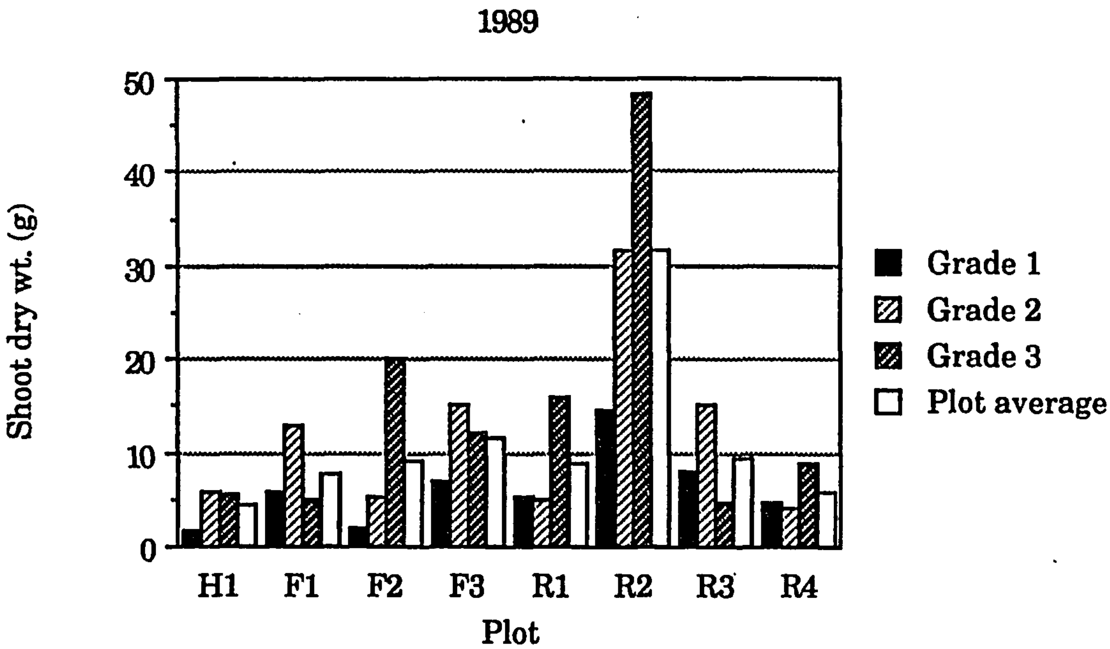


Figure 23. Average dry weights of shoots for seedlings excavated in 1989, by plot and by root grade

between plot F3 and plot R3 ($p < 0.01$) and between plots F3 and R4 versus plots R1 and R2 ($p < 0.05$) in 1987 (Figure 22). In 1988, significant differences ($p < 0.05$) for average shoot dry weight occurred between plots H1 and F1 versus plot R2 (also shown in Figure 22). For trees excavated in 1989, average shoot dry weights for seedlings from plot R2 were significantly greater ($p < 0.01$) than shoot dry weights of seedlings from all other plots (Figure 23). Most of the difference was due to size of the grade three seedlings excavated from plot R2 in 1989, which were larger than the average grade three seedlings on that plot in terms of field measurements of height and diameter that year.

Root system characteristics

Data for seedling root systems was only available from harvested trees, and as earlier suggested, for plot comparisons sampled trees were less representative of the whole than in Part I. Root system parameters will be discussed in a general sense, recognizing that some degree of subsampling error may have affected the results. Mean values for the original root grade of seedlings excavated in 1987, 1988, and 1989 on the various plots are given in Table 8 to demonstrate that there were few significant differences in initial average root grade between years or between plots for the seedlings analyzed. The only statistically significant (at the .05 level) differences in initial average root grade of excavated trees occurred between seedlings from plot H1 which had higher initial root grades than those from plots F3 and R1 in 1989.

Variation in length of longest lateral between planting sites was not significant for seedlings excavated in 1987 and 1988. However, seedlings excavated from plots F1 and R4 had significantly shorter laterals than those excavated from plot R2 ($p < 0.01$ level) and those excavated from plot F3 ($p <$

0.05) in 1989 (Table 8). Both plots F1 and R4 were upland sites with strongly structured subsoil material in which root extension might have been hindered somewhat under drought conditions. Likewise, no significant differences in root mass width between plots was apparent for seedlings excavated in 1987. Average root mass width of seedlings excavated from plot H1 was significantly smaller than that from plot R2 ($p < 0.05$) in 1988. Average root mass width for seedlings excavated in 1989 from plot R2 was greater than that for all other plots except plot R3. However, this difference may have been due to method of excavation, since plots R2 and R3 were hand-dug and all other seedlings were excavated using the tree spade in 1989.

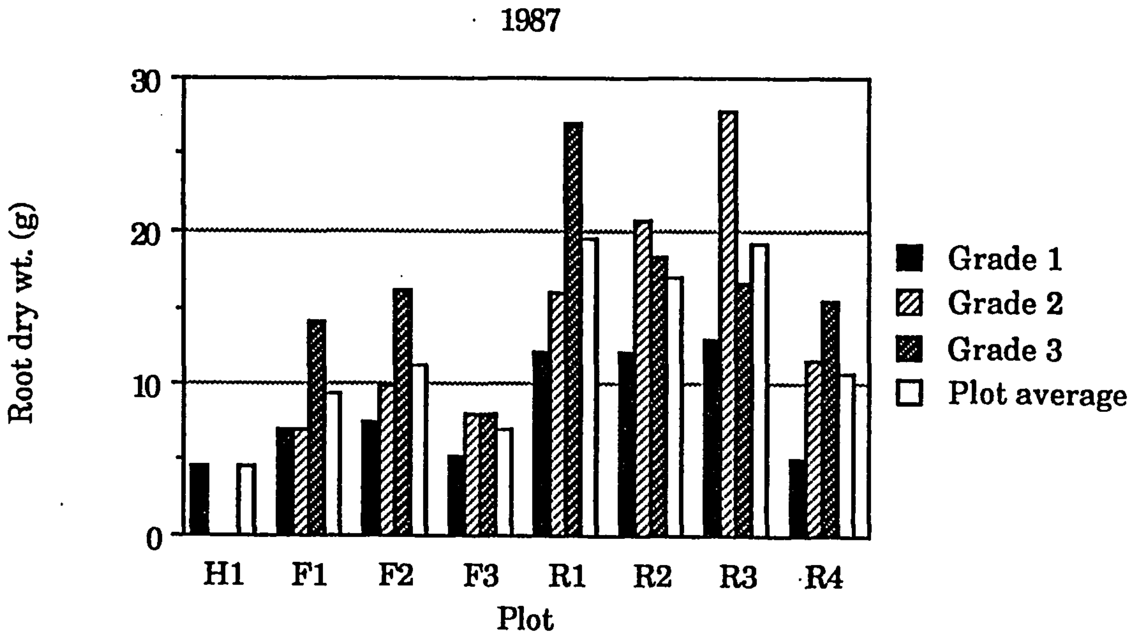
Seedlings excavated from plot R1 had significantly greater values for new root grade in 1987 than seedlings from plots H1, F1, F3, or R4 (Table 8). These values cannot be explained on the basis of the formation of greater numbers of callus roots, since the average number of callus roots counted on seedlings from R1 was actually lower than numbers for most other plots. This may have been due to formation and thickening of other new first-order lateral roots along the taproot or due to thickening of first-order lateral roots that were present at the time of grading but less than 1 mm in diameter. Seedlings from plot R3 had a significantly higher value for new root grade than seedlings from plot F3, but this difference could be explained by greater numbers of callus roots being produced on seedlings excavated from plot R3. In fact, the average value for callus roots for plot R3 is significantly greater than for plots F1 and F3. For seedlings excavated in 1988 and 1989, no significant differences between plots were calculated for mean new root grade or average numbers of callus roots.

Total numbers of first-order lateral roots were significantly higher on plot R1 than on all other plots in 1987 (Table 8). No significant differences between plots were calculated for total numbers of first-order roots in 1988 or 1989. Total numbers of second-order laterals were also higher for seedlings excavated from R1 in 1987, although the amount of variability in this characteristic prevented calculation of significant differences at the 0.01 level. Plot R1 had the deepest A horizon materials and fairly high surface and subsurface total C contents. Other workers have reported that high "concentrations" of roots were correlated with levels of soil organic matter (e.g., Lyr and Hoffman, 1967; Black, 1968). Seedlings excavated in 1988 from plot H1 had greater numbers of second-order roots versus plot F1 ($p < 0.05$) and plot R2 ($p < 0.01$). However, H1 seedlings excavated in 1988 also had higher values of original and new root grade than seedlings on other plots. In 1989, F2 seedlings had significantly greater numbers of second-order lateral roots than seedlings from plots H1, F1, F3, R3, and R4 ($p < 0.05$). These seedlings also had relatively high values for original root grade and therefore may not have been a representative sample.

Data for taproot dry weights of excavated seedlings by plot and root grade are shown in Table 8. Differences in average seedling taproot weight between plots were significant for all three years. In 1987, taproot dry weights were significantly greater for seedlings excavated from plots R1, R2, and R3 than for seedlings excavated from F1, F2, and F3 (for most comparisons, $p < 0.01$). Plot H1 was excluded from the analysis due to missing values. In 1988, seedlings from plot R2 had significantly greater taproot dry weights than seedlings from H1 or F1 (Table 8). In 1989, seedlings from plot R2 had significantly greater taproot dry weights than seedlings on all other plots. Differences in lateral root weight were not significant in 1987 and 1988, but differences in 1989 between seedlings from plot R2 versus seedlings from H1, F1, R3, and R4 were significant ($p < 0.05$). Results for total root weight were significant in two of three years (Table 8 and Figures 24 and 25). In 1987, total root dry weight for seedlings from plot F3 was significantly lower than for seedlings excavated from plots R1, R2, and R3 (H1 was excluded from the analysis because of missing values). Seedlings from plots F2 and R4 had significantly lower total root dry weights than those excavated from plot R3. Differences in total root dry weight for 1988 were not significant. In 1989, only seedlings from plot F3 were, on the average, not significantly different compared with seedlings harvested from plot R2.

Correlations between seedling characteristics and selected soil properties

The CORR procedure of SAS was used to generate partial correlation matrices to analyze relationships between means for seedling characteristics for each year which were found to vary significantly between plots (presented in Table 8) and mean soil properties. Weighted means for soil properties as described earlier (and given in Appendix C) were used for this procedure. Selected results of the CORR procedure are summarized in Table 9. For trees excavated in 1987, mean heights (and plant part dry weights) were significantly and negatively correlated with surface and subsurface soil pH (similar to results reported for all trees). Length of longest lateral was significantly and negatively related to surface horizon total N level, and significantly and positively related to subsoil bulk density. The negative relationship between root length and soil N levels (and, in fact, P and K levels)



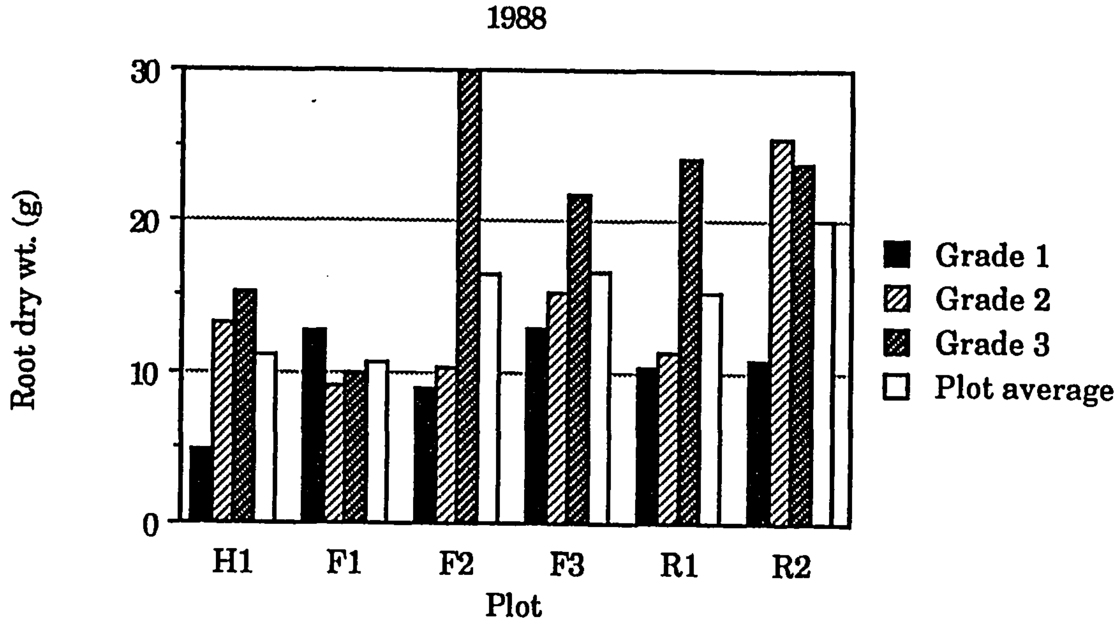


Figure 24. Average dry weights of root systems for seedlings excavated in 1987 and 1988, by plot and by root grade

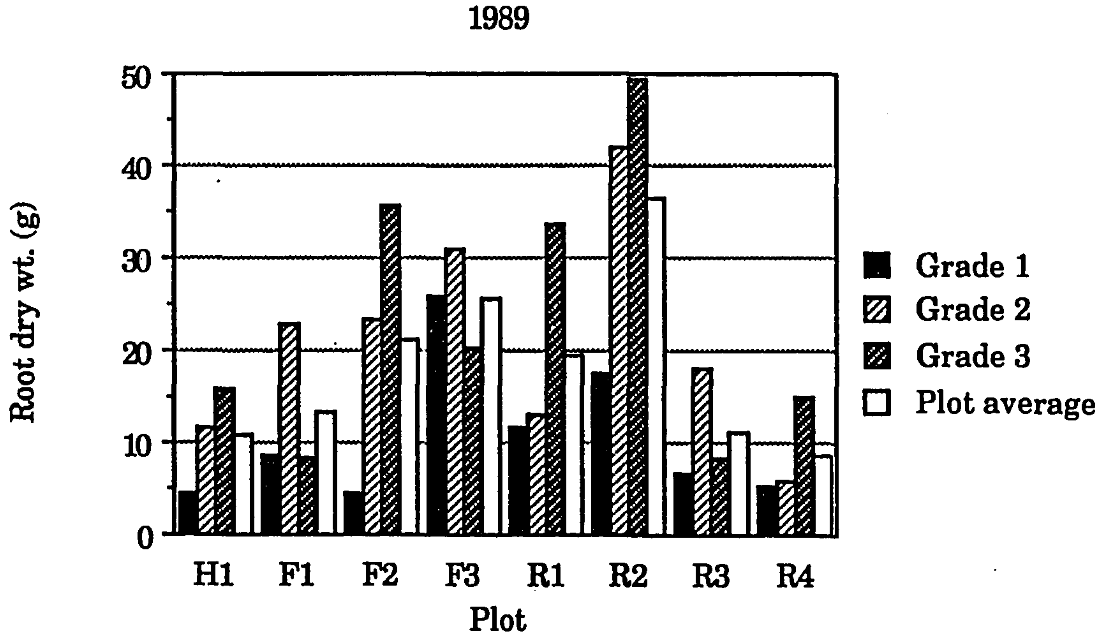


Figure 25. Average dry weights of root systems for seedlings excavated in 1989, by plot and by root grade

Table 9. Correlation coefficients and probabilities of larger correlation coefficients for seedling means from Table 8 and weighted means for selected soil properties, by year

	Seedling characteristics								
Soil parameters	Height	Crown depth	Longest lateral	Width roots	New root grade	Tot. 2nd lats	Dry wt. shoot	Dry wt. laterals	Dry wt. root
					1987				
Depth A	-0.12[a]	x	-0.22	-0.17	0.10	0.26	0.18	0.46	-0.07
	0.77[b]	x	0.59	0.69	0.81	0.53	0.67	0.29	0.87
Srf[c] C	-0.55	x	-0.78	-0.21	-0.53	-0.56	-0.59	-0.27	-0.43
	0.16	x	0.02	0.61	0.17	0.15	0.13	0.56	0.28
Sb C	-0.09	x	-0.32	0.06	0.16	0.32	-0.01	0.80	0.04
	0.82	x	0.44	0.89	0.70	0.43	0.97	0.03	0.92
Srf N	-0.30	x	-0.71	0.14	-0.36	-0.44	-0.45	-0.31	-0.36
	0.47	x	0.05	0.75	0.37	0.27	0.26	0.50	0.38
Srf pH	-0.74	x	-0.75	-0.30	-0.72	-0.57	-0.80	-0.53	-0.75
	0.04	x	0.03	0.47	0.04	0.13	0.02	0.22	0.03
Sb pH	-0.75	x	-0.50	-0.61	-0.67	-0.56	-0.82	-0.57	-0.80
	0.03	x	0.20	0.11	0.07	0.15	0.01	0.19	0.02
Sb BD	0.64	x	0.74	0.07	0.61	0.58	0.50	0.33	0.48
	0.08	x	0.03	0.87	0.11	0.13	0.21	0.46	0.23
Srf SA	0.42	x	0.17	0.37	0.45	0.29	0.61	0.38	0.63
	0.30	x	0.69	0.37	0.27	0.49	0.11	0.40	0.10
Sb SA	-0.04	x	0.06	-0.16	-0.18	-0.04	0.008	0.23	-0.07
	0.92	x	0.88	0.69	0.66	0.92	0.98	0.62	0.87
Sb CL	0.21	x	0.04	0.01	0.64	0.49	0.30	0.35	0.48
	0.62	x	0.92	0.97	0.09	0.22	0.47	0.44	0.23

[a]Pearson correlation coefficient.

[b]Probability of a greater value of the coefficient.

[c]Srf refers to surface (A) horizon values, Sb refers to subsurface (B) horizon values.

Table 9. (Continued)

Soil parameters	Height	Crown depth	Longest lateral	Width roots	New root grade	Tot. 1st lats	Dry wt. shoot	Dry wt. laterals	Dry wt. root
				Seedling characteristics					
					1988				
Depth A	0.16	0.73	0.90	-0.14	0.32	0.63	0.20	0.18	0.04
	0.76	0.10	0.01	0.80	0.54	0.18	0.70	0.73	0.94
Srf C	-0.30	0.41	0.61	0.35	0.65	0.91	0.09	0.04	0.16
	0.58	0.42	0.20	0.50	0.16	0.01	0.86	0.94	0.76
Sb C	-0.07	0.44	0.61	-0.47	0.02	0.28	-0.17	-0.31	-0.37
	0.89	0.38	0.20	0.35	0.98	0.58	0.74	0.55	0.47
Srf N	-0.14	0.02	0.20	0.67	0.83	0.80	0.26	-0.13	0.34
	0.80	0.97	0.70	0.15	0.04	0.05	0.62	0.81	0.51
Srf pH	-0.65	0.69	0.69	-0.33	0.22	0.43	-0.44	-0.04	-0.29
	0.16	0.13	0.13	0.52	0.68	0.39	0.39	0.93	0.58
Sb pH	-0.69	0.51	0.49	-0.48	-0.16	0.17	-0.57	-0.003	-0.43
	0.13	0.30	0.32	0.33	0.76	0.75	0.24	0.99	0.40
Sb BD	0.79	-0.30	-0.32	0.50	0.02	-0.14	0.68	0.49	0.58
	0.06	0.57	0.53	0.31	0.97	0.80	0.13	0.33	0.23
Srf SA	0.44	-0.67	-0.49	0.35	0.03	-0.03	0.33	-0.37	0.11
	0.38	0.14	0.32	0.50	0.95	0.96	0.53	0.47	0.84
Sb SA	-0.48	0.04	0.33	-0.05	0.10	0.61	-0.29	-0.40	-0.34
	0.33	0.94	0.52	0.93	0.85	0.20	0.58	0.43	0.51
Sb CL	0.84	-0.003	0.02	0.08	-0.06	-0.43	0.57	0.28	0.31
	0.04	0.99	0.97	0.88	0.91	0.78	0.24	0.59	0.55

corresponds with other reports (e.g., Lyr and Hoffman, 1967) of long roots which are not highly branched that form under conditions of lower nutrient levels. The positive relationship between length of laterals and bulk density was somewhat unexpected, although it may be that strength of soil structural units per se or soil water content are greater impediments to root elongation than soil bulk density. Overall, positive relationships between numbers of roots and surface and subsurface levels of N, P, and K were calculated for 1987 data, although not many of them were significant. Although numbers of first- and second-order lateral roots were not significantly related to soil C content, dry weight of lateral roots was significantly and positively correlated with total carbon in subsurface soil horizons. Similar results have been reported by Lyr and Hoffman (1967). Dry weights of shoots and roots in 1987 were significantly and positively correlated with surface horizon sand content. Dry weight of roots, however, was negatively correlated with subsoil sand contents.

For seedlings excavated in 1988, mean height was most strongly correlated with subsoil clay content. Crown depth and lateral root length were positively correlated with depth of A horizon materials. Again, length of laterals and width of root mass were negatively correlated with N, P, and K levels. However, new root grade and total numbers of first-order laterals were positively correlated surface horizon N levels. Total numbers of first-order roots were also significantly and positively related to surface soil C levels (although relationships between root dry weights and soil C were not significant). Total numbers of second-order lateral roots were significantly and positively related to surface and subsurface soil pH.

Few significant relationships between soil properties and seedling characteristics were calculated for seedlings excavated in 1989. Again, this may have been due to the overriding influence of factors not included in the analysis, such as soil moisture levels during the extended drought.

SUMMARY AND CONCLUSIONS

1. Average survival rates differed significantly among sites. In addition, significant variation occurred for survival rates within root grade 1 and root grade 3 seedlings on different sites. At the end of the third year after outplanting, plots H1 and R4 had significantly lower survival rates compared with all other plots. The influence on seedling survival of site factors which affected moisture availability was pronounced because of the 1988-1989 drought. Variation in performance of seedlings from the three root grade groups on different sites suggests that prescription planting of northern red oak bare-root stock according to outplanting site characteristics may be advisable. Small seedlings with few roots and large seedlings with small root to shoot ratios were not successful under relatively harsh conditions, whereas seedlings with at least 5 permanent lateral roots and relatively high root to shoot ratios had better survival rates on a range of sites.

2. Significant differences in height growth between plots were already apparent at the end of the first growing season. At the end of the third growing season, remaining seedlings on plots R2 and R3 were on the average significantly taller than seedlings on all other plots. Significant differences in seedling diameter were also noted by the end of the third growing season. Average diameters for seedlings remaining on plots H1 and F1 were significantly smaller than average diameters for seedlings from plots R1, R2, R3, F2, or F3.

3. Based on partial correlation analyses, seedling height and diameter growth were generally positively correlated with bulk density and subsurface clay contents, and negatively correlated with surface and subsurface pH, surface

horizon P and K levels, and subsurface sand contents. The general lack of significant correlations between soil properties and seedling growth was probably due small sample size and due to the overriding effect of factors related to extreme drought conditions (which were not included in the analysis).

4. Measurements of harvested trees indicated statistical differences between outplanting sites for shoot characteristics (height, diameter, and stem and total shoot dry weight) and root characteristics (length of longest lateral, width of root mass, new root grade, total first-order lateral roots,total second-order lateral roots, and taproot and total root dry weights). Generally, third year dry weight data for excavated trees corroborated evidence from field measurements that seedlings on plot R2 were significantly larger than seedlings on all other plots. This was proabably due to the relatively protected physiographic position of plot R2, as well as soil characteristics that may have afforded more available moisture to seedlings.

5. For harvested trees, partial correlation analyses generally indicated positive relationships between seedling shoot and root system characteristics and soil properties including subsoil clay content, surface soil C content, and bulk density. Again, few relationships were statistically significant.

LITERATURE CITED

Barden, C. J., and T. W. Bowersox. 1989. The effect of root pruning treatments on red oak seedling root growth capacity. U.S.D.A. For. Serv. Gen. Tech. Rep. NC-132, pp. 115-119. North Central For. Exp. Stn, St Paul, MN.

Barnett, J. P. 1988. Site preparation, containers, and soil types affect field performance of loblolly pine and longleaf pine seedlings. U.S.D.A. For. Serv. Gen. Tech. Rep. SO-74. So. For. Exp. Stn., New Orleans, LA.

Black, C. A. 1968. Soil-Plant Relationships. J. Wiley and Sons, New York, 792 pp.

Blake, G. R. 1965. Bulk density. Pp. 374-390 in Black, C. A., et al., eds., Methods of Soil Analysis, Part 1. Agronomy Monographs, American Society of Agronomy, Madison, WI.

Borchert, R. 1973. Simulation of rhythmic tree growth under constant conditions. Physiol. Plant. 29:173-180.

Borchert, R. 1975. Endogenous shoot growth rhythms and indeterminate shoot growth in oak. Physiol. Plant. 35:152-157.

Burdett, A. N., D. G. Simpson, and C. F. Thompson. 1983. Root development and plantation establishment success. Plant and Soil 71:103-110.

Champion, R. A., and K. P. Barley. 1969. Penetration of clay by root hairs. Soil Sci. 108:402-407.

Cockroft, B., and J. M. Tisdall. 1974. Soil management, soil structure, and root activity. Pp 387-391 in Carson, E. W., ed., The Plant Root and its Environment. Univ. Press of Virg., Charlottesville, VA.

Coutts, M. P. 1987. Developmental processes in tree root systems. Can. J. For. Res. 17:761-767.

Coutts, M. P., and G. J. Lewis. 1983. When is the structural root system determined in Sitka spruce? Plant and Soil 71:155-160.

Davis, G. R., W. A. Neilsen, and J. G. McDavitt. 1983. Root distribution of Pinus radiata related to soil characteristics in five Tasmanian soils. Aust. J. Soil Res. 21:165-171.

Dexter, A. R. 1987. Mechanics of root growth. Plant and Soil 98:303-312.

Dickson, R. E. 1991. Episodic growth and carbon physiology in northern red oak. Pp. 117-124 in Proc. the Oak Resource in the Upper Midwest Conf., Winona, MN.

Dickson, R. E., and P. T. Tomlinson. 1989. Changes in carbon fixation, partitioning, and allocation during episodic growth in northern red oak. P. 4 in J. vanSambeek and M. Larson, eds., Abstracts of the Oak Seedling Physiology Conf., North Central For. Exp. Stn., St Paul, MN.

Dixon, R. K., H. E. Garrett, G. S. Cox, and S. G. Pallardy. 1984. Mycorrhizae and reforestation success in the oak-hickory region. Pp. 301-309 in Duryea, M. L., and W. Brown, eds., Seedling Physiology and Reforestation Success. Nijhoff/Dr. W. Junk Pub., Boston, MA. 326 pp.

Drew, A. P., and F. T. Ledig. 1980. Episodic growth and relative shoot:root balance in loblolly pine seedlings. Ann. Bot. 45:143-148.

Duryea, M. L. 1984. Nursery cultural practices: Impacts on seedling quality. Pp. 143-164 in Duryea, M. L., and T. D. Landis, eds., Forest Nursery Manual: Production of Bareroot Seedlings. Forest Research Lab, Oregon State Univ./Martinus/Nijhoff/Dr. W. Junk, Pub., Corvallis, OR and Boston, MA. 386 pp.

Duryea, M. L. 1985. Evaluating seedling quality: Importance to reforestation. Pp. 1-4 in Duryea, M. L., ed., Evaluating Seedling Quality: Principles, Procedures and Predictive Abilities of Major Tests. Oregon State Univ. Corvallis, OR.

Dwyer, L. M., D. W. Stewart, and D. Balchin. 1988. Rooting characteristics of corn, soybeans, and barley as a function of available soil water and soil physical characteristics. Can. J. Soil Sci. 68:121-132.

Eschner, A. R. 1952. Growth and composition of oak stands on the Brayton Forest in relation to soil and topography. Unpublished M.S. Thesis, Iowa State Univ., Ames, IA.

Farmer, R. E. 1975. Dormancy and root regeneration of northern red oak. Can. J. For Res. 5:176-185.

Faulkner, H., and D. C. F. Fayle. 1979. Root development of three 5-year old Euramericana poplar clones at two plantation sites. Pp in Fayle, D. C. F., L. Zsuffa, and H. W. Anderson, eds, Report #8 in Poplar Research, Management and Utilization in Canada. For. Res. Infor. Paper 102, Ontario Ministry of Forests, Ontario.

Fehrenbacher, J. B., and H. J. Snider. 1954. Corn root penetration in Muscatine, Elliott, and Cisne soils. Soil Sci. 77:281-291.

Fehrenbacher, J. B., B. W. Ray, and W. M. Edwards. 1965. Rooting volume of corn and alfalfa in shale-influenced soils in northwestern Illinois. Soil Sci. Soc. Amer. Proc. 29:591-594.

Feldman, L. J. 1984. Regulation of root development. Ann. Rev. Plant Physiol. 35:223-242.

Feret, P. P. Unpublished manuscript. Interim Report for Hardwood Quality Nursery Cooperative, Dept. of Forestry, Iowa State University, Ames, IA.

Fogel, R. 1983. Root turnover and productiviy of coniferous forests. Plant and Soil 71:75-85.

Fowells, H. A. 1965. Silvics of Forest Trees of the United States. U.S.D.A. For. Serv. Agric. Handbook #271, U.S.D.A., Washington, D.C. 762 pp.

Fralish, J. S., and O. L. Loucks. 1975. Site quality evaluation models for aspen (*Populus tremuloides*) in Wisconsin. Can. J. For. Res. 5:523-528.

Gale, M. R., and D. F. Grigal. 1986. Modification of a soil productivity index model based on rooting suitability for forested sites. Agron. Abstracts p. 260-261.

Gale, M. R., and D. F. Grigal. 1987. Vertical root distributions of northern tree species in relation to successional status. Can. J. For. Res. 17:829-834.

Gilman, E. F. 1990. Tree root growth and development. I. Form, spread, depth, and periodicity. J. Environ. Hort. 8:215-220.

Gjerstad, D. H., L. R. Nelson, J. H. Dukes, and W. A. Retzlaff. 1984. Growth response and physiology of tree seedlings as affected by weed control. Pp. 247-258 in M. L. Duryea and W. Brown, eds., Seedling Physiology and Reforestation Success. Nijhoff/Dr. W. Junk, Boston.

Grossnickle, S. C., and T. J. Blake. 1987. Water relation patterns of bare-root and container jack pine and black spruce seedlings planted on boreal cut-over sites. New Forests 1:101-107.

Haasis, F. W. 1921. Relations between soil type and root form of western yellow pine seedlings. Ecology 2:292-303.

Hay, R. L., R. D. Hammer, and J. P. Conn. 1987. Soil properties dominate yellow-poplar seedling growth. S. Jour. Appl. For. 11:119-123.

Hobbs, S. D. 1984. The influence of species and stocktype selection on stand establishment: An ecophysiological perspective. Pp. 179-224 in Duryea, M. L., and W. Brown, eds., Seedling Physiology and Reforestation Success. Nijhoff/Dr. W. Junk Pub. Boston, MA.

Holch, A. E. 1931. Development of roots and shoot of certain deciduous tree seedlings in different forest sites. Ecology 12:259-298.

Insley, H., and G. P. Buckley. 1985. The influence of dessication and root pruning on the survival and growth of broadleaved seedlings. J. Hort. Sci. 60:377-387.

Johnson, P. S. 1988. Undercutting alters root morphology and improves field performance of northern red oak. Proc. Tenth North American For. Biol. Workshop, Univ. British Columbia, Victoria, B. C.

Khajjidoni, S. T., and S. B. Land. 1988. Family effects on root characteristics and root growth potential of American sycamore seedlings. Pp. 108-115 in Proc. Tenth North American Forest Biology Workshop, 1988, Univ. of British Columbia, Victoria, B.C.

Kochendorfer, J. N. 1973. Root distribution under some forest types native to West Virginia. Ecology 54:445-448.

Kormanik, P. P. 1986. Lateral root morphology as an expression of sweetgum seedling quality. For. Sci. 32:595-604.

Kormanik, P. P. 1988. Frequency distribution of first-order lateral roots in forest tree seedlings: silvicultural implications. Pp 101-105 in U.S.D.A. For. Serv. Gen Tech. Rep. SO-74. Southern Forest Experiment Stn., New Orleans, LA.

Kormanik, P. P. 1989. Importance of first-order lateral roots in the early development of forest tree seedlings. Pp. 157-169 in Vancura, V., and F. Kunc, eds., Interrelationships Between Microorganisms and Plants in Soil. Academia Publishing House of the Czechoslovak Academy of Sciences, Praha, Czechoslovakia.

Kormanik, P. P., and J. L. Ruehle. 1989. First order lateral root development: something to consider in mother tree and progeny assessment. Pp. 220-227 in Proc. Twentieth Southern Forest Tree Improvement Conference, Charleston, S.C. Pub. #42, Southern Forest Tree Improvement Committee.

Kormanik, P. P., J. L. Ruehle, and H. D. Muse. 1988. Frequency distributions of seedlings by first-order lateral roots: a phenotypic or genotypic expression. Pp. 181-187 in Proc. Thirty-first N.E. Forest Tree Improvement Conf. Penn. State Univ., Univ. Park, PA.

Kramer, P. C., and H. C. Bullock. 1966. Seasonal variations in the proportions of suberized and unsuberized roots of trees in relation to the absorption of water. Amer. J. Bot. 53:200-204.

Kramer, P. J., and T. T. Kozlowski. 1979. Physiology of Woody Plants. Academic Press, Boston, MA. 811pp.

Langlois, C. G., L. Godbout, and J. A. Fortin. 1983. Seasonal variation of growth and development of roots of 5 second year conifer species in the nursery. Plant and Soil 71:55-62.

Larson, M. M. 1980. Effects of atmospheric humidity and zonal water stress on initial growth of planted northern red oak seedlings. Can. J. For. Res. 10:549-554.

Larson, M. M., and F. W. Whitmore. 1970. Moisture stress affects root regeneration and early growth of red oak seedlings. For. Sci. 16:495-498.

Logsdon, S. D., J. C. Parker, and R. B. Reneau, Jr. 1987. Root growth as influenced by aggregate size. Plant and Soil 99:267-275.

Lunt, H. A. 1939. Soil characteristics, topography, and lesser vegetation in relation to site quality of second growth oak stands in Connecticut. Jour. Agr. Res. 59:407-428.

Lyford, W. H. 1980. Development of the root system of northern red oak (*Quercus rubra* L.). Harvard Forest Paper No. 21, Harvard University, Petersham, MA. 30 pp.

Lyr, H., and G. Hoffman. 1967. Growth rataes and growth periodicity of tree roots. Pp 181-236 in Romberger, J. A., and P. Mikola, eds., International Review of Forestry Research Vol II. Academic Press, New York, NY.

McCormick, L. H., and T. W. Bowersox. 1989. Artificial regeneration of oaks: Problems and potential. P. 22 in J. vanSambeek and M. Larson, eds., Abstracts of the Oak Seedling Physiology Conf., North Central For. Exp. Stn. St. Paul, MN.

McCully, M. E. 1975. The development of lateral roots. Pp. 105-124 in J. G. Torrey and D. T. Clarkson, eds., The Development and Function of Roots. Third Cabot Symposium. Academic Press, New York, NY.

Mirreh, H. F., and J. W. Ketcheson. 1973. Influence of soil water matric potential and resistance to penetration on corn root elongation. Can. J. Soil Sci. 53:383-388.

Olsen, S. R., and L. A. Dean. 1965. Phosphorus. Pp. 1035-1048 in Black, C. A., et al., eds., Methods of Soil Analysis. Agronomy Monographs 9, Part 2.. American Society of Agronomy, Madison, WI.

Olson, D. F., and R. M. Hooper. 1972. Northern red oak plantings survive well in Southern Appalachians. Tree Planter's Notes 23:16-18.

Overton, R. P. 1989. Conservation Reserve Program tree planting in the northeastern U.S. The 1989 update. Proc. Northeastern Area Nurserymen's Conf. Division of Forest Resources, Mason State Tree Nursery, Topeka, IL.

Peech, M. 1965. Hydrogen-ion activity. Pp. 914-925 in Black, C. A., et al., eds, Methods of Soil Analysis. Agronomy Monographs 9. Part 2. American Society of Agronomy, Madison, WI.

Ponder, F., Jr. 1979. Soil structure and mycorrhizae encourage black walnut growth on old fields. North Central For. Exp. Stn. Res. Note NC-249. U.S.D.A. For. Serv., St. Paul, MN.

Pratt, P. F. 1965. Potassium. Pp. 1022-1030 in Black, C. A., et al., eds., Methods of Soil Analysis. Agronomy Monographs 9, Part 2. American Society of Agronomy, Madison, WI.

Racey, G. D. 1985. A comparison of planting stock characterization with root area index, volume, and dry weight. For. Chron. 61:64-70.

Reich, P. B., R. Teskey, P. Johnson, and T. Hinckley. 1980. Periodic root and shoot growth in oak. For. Sci. 26:590-598.

Rietveld, W. J., and J. W. van Sambeek. 1989. Relating black walnut planting stock quality to field performance. U.S.D.A. For. Serv. Gen Tech. Rep. NC-132, pp. 162-169.

Ritchie, G. A., and J. R. Dunlap. 1980. Root growth potential: Its development and expression in forest tree seedlings. New Z. J. For. Sci. 10:218-248.

Sander, I. L. 1977. Manager's Handbook for Oak in the North Central States. North Central For. Exp. Stn. Gen. Tech. Rep. NC-37, U.S.D.A. For. Serv., St. Paul, MN 35pp.

Sandor, J. A. Unpublished manuscript. Particle size analysis.

SAS Institute, Inc. 1985. SAS User's Guide: Basics, Version 5 Edition. SAS Institute, Cary, NC.

Schultz, R. C. 1989. Cultural practices and oak seedling root development. P. 10 in J. van Sambeek and M. Larson, eds., Abstracts of the Oak Seedling Physiology Symposium. North Central For. Exp. Stn., St Paul, MN.

Schultz, R. C., and J. R. Thompson. 1987. What is the Hardwood Nursery Cooperative doing? Pp. 103-106 in Proc. Northeastern Area Nurserymen's Meeting, Hayward, WI.

Schultz, R. C., and J. R. Thompson. 1989. Nursery cultural practices that improve hardwood seedling root morphology. Pp. 17-39 in Proc. Northeastern Area Nurserymen's Conf., Peoria, IL.

Schultz, R.C., and J. R. Thompson. 1990. Nursery cultural practices that improve hardwood seedling root morphology. Tree Planter's Notes 41:21-32.

Schultz, R. C., and J. R. Thompson. 1991. The quality of oak seedlings needed for successful artificial regeneration in the central states. Pp. 180-186 in Proc. Oak Resource in the Upper Midwest Conf., Winona, MN.

Soil Survey Staff. 1981. Examination and description of soils in the field. Chapter 4, Revised Soil Survey Manual (430-V). U.S.D.A. Soil Conservation Service.

South, D. B., J. N. Boyer, and L. Bosch. 1985. Survival and growth of Loblolly pine as influenced by seedling grade: 13 year results. S. Jour. Appl. For. 9:76-81.

Spencer, J. S., and N. P. Kingsley, 1991. The oak resource in the upper midwest: An overview. Pp. 11-17 in Proc. The Oak Resource of the Upper Midwest Conf., Winona, MN.

Stein, W. I. 1978. Naturally developed seedling roots of five western conifers. In vanEerden, E., and J. M. Kinghorn, eds., Root Form of Planted Trees. Brit. Columbia Ministry of Forests/Canadian Forestry Service Joint Rep. #8.

Stolzy, L. H., and K. P. Barley. 1968. Mechanical resistance encountered by roots entering compact soils. Soil Sci. 105:297-301.

Stone, E. C., J. L. Jenkinson, and S. L. Krugman. 1962. Root-regenerating potential of Douglas-fir seedlings lifted at different times of the year. For. Sci. 8:288-297.

South, D. B., H. S. Larsen, H. M. Williams, and J. N. Boyer. 1988. Use of seedling size as a covariate for root growth potential studies. U.S.D.A. For. Serv. Gen. Tech. Rep. SO-74. Pp. 89-93. S. For. Exp. Stn., New Orleans, LA.

Sutton, R. F. 1980a. Planting stock quality, root growth capacity, and field performance of 3 boreal conifers. New Z. J. For. Sci. 10:54-71.

Sutton, R. F. 1980b. Root system morphogenesis. New Z. J. For. Sci. 10:264-292.

Sutton, R. F. 1983. Root growth capacity: Relationship with field root growth and performance in outplanted jack pine and black spruce. Plant and Soil 71:111-122.

Stroempl, G. 1985. Grading northern red oak planting stock. Tree Planter's Notes 36:15-18.

Stroempl, G. 1989. Northern red oak regeneration program in Ontario: an overview. P. 25 in Abstracts of the Oak Seedling Physiology Symposium. North Central For. Exp. Stn. St. Paul, MN.

Taylor, H. M. 1974. Root behavior as affected by soil structure and strength. Pp. 271-291 in Carlson, E. W., ed., The Plant Root and its Environment. Univ. Press of Virg., Charlottesville, Virg.

Teclaw, R. M., and J. G. Isebrands. 1991. Artificial regeneration of northern red oak in the lake states. Pp. 187-197 in Proc. The Oak Resource in the Upper Midwest Conf., Winona, MN.

Thompson, B. E. 1985. Seedling morphological evaluation: What you can tell by looking. Pp. 59-71 in M. L. Duryea, ed., Evaluating Seedling Quality: Principles, Procedures and Predictive Abilities of Major Tests. Oregon State University, Corvallis, OR.

Thompson, J. R., and R. C. Schultz. 1989. Red oak seedling development after outplanting. Pp. 97-105 in Proc. Northeastern Area Nurserymen's Conf., Peoria, IL.

Thompson, J. R., and R. C. Schultz. Unpublished manuscript. Root and shoot development of nursery-grown northern red oak (*Quercus rubra* L.) seedlings.

Thomson, G. W. 1956. Growth of plantation black walnut in southeastern Iowa as related to certain soil properties. Doctoral dissertation, Iowa State Univ., Ames. IA.

Turner, L. M. 1936. A comparison of roots of southern shortleaf pine in 3 soils. Ecology 17:649-658.

Venator, C. R. 1983. First-year survival of morphologically graded loblolly pine seedlings in central Louisiana. Tree Planter's Notes 34:34-36.

Walter, N. F., G. R. Hallberg, and T. E. Fenton. 1978. Particle size analysis by the Iowa State University Soil Survey Laboratory. Pp 61-74 in Hallberg, G. R., ed., Standard Procedures for Evaluation of Quaternary Materials in Iowa. Iowa Geological Survey Tech. Info. Series #8, Iowa City, IA.

Warnaars, B. C., and B. W. Eavis. 1972. Soil physical conditions affecting seedling root growth. II. Mechanical impedance, aeration, and moisture availability as influenced by grain size distribution and moisture content in silica sands. Plant and Soil 36:623-634.

Webb, D. P., and E. B. Dumbroff. 1978. Root growth in seedlings of *Acer saccharum*. In A. Riedacker and J. Gagnaire, eds., Physiologie des Racines et Symbioses. Nancy, France.

Wright, S. L., R. W. Hall, and J. W. Peacock. 1989. Effect of simulated insect damage on growth and survival of northern red oak (*Quercus rubra* L.) seedlings. Environ. Entomol. 18:235-239.

Yen, C. P., C. H. Pham, G. S. Cox, and H. E. Garrett. 1978. Soil depth and root development patterns of Missouri black walnut and several Taiwan hardwoods. In vanEerden, E., and J. M. Kinghorn, eds., Proc. of the Root Form of Planted Trees Symposium. Brit. Col. Ministry of Forests/Canadian Forestry Service Joint Rep. #8, Victoria, B. C.

ACKNOWLEGMENTS

A long list of persons and organizations contributed to the completion of this dissertation. Thanks to you all!

This work was financially supported by U.S.D.A. Forest Service Focus Funds, and McIntire-Stennis Funds. Seedlings, grading facilities, and use of the tree spade were graciously provided by Mr. Jerry Grebasch, at the Iowa Department of Natural Resources State Forest Tree Nursery in Ames.

Many thanks are due to those who spent hours as tree graders, planters, measurers, excavators, and soil describers and samplers : Dick Schultz, John Kean, Rod Maharry, Michael Thompson, Rick Meilan, Jeff Roe, Jason Morrison, Rob Hilken, Joe Dwyer, Joe Colletti, Kwan Choi, Janel Hall, and Priscilla Licht.

Thanks are due to Bill Effland, Jon Sandor, Faruque Kahn, Ken Trytek, and Michael Thompson for providing equipment and assistance with soil laboratory analyses.

I would also like to acknowledge the participation of members of my graduate committee, Drs. Schultz, Hall, Mize, Loynachan, and Sandor in the design of my study and in thoughtfully reviewing this dissertation.

Daughter Katherine arrived sometime in the middle of all of this, and certainly put up with some craziness during her first 3 years of life. Thanks to her, and to Michael (a.k.a. Mr. Mom), for "keeping the home fires burning" when I was away. Very heartfelt appreciation also goes to my mother and father (Grandma Bobby and Grandpa Bill) for their support, encouragement, and many treks to Iowa to take charge of the ranch and the kiddo.

APPENDIX A. ROOT GROWTH POTENTIAL (RGP) EVALUATION OF RED OAK SEEDLINGS

Background

In early work with conifer seedling root systems, Stone (1955) emphasized the importance of the physiological condition of planting stock, focusing on the capacity of seedlings to rapidly produce new roots after transplanting (which he referred to as root regeneration potential, or RRP). Since that time, several workers have examined the RRP (also known as root growth potential, RGP, or root growth capacity, RGC) of a number of additional conifer species and some hardwood species (e.g. Larson, 1970, 1975; Farmer, 1975; van den Driessche, 1978; Feret and Kreh, 1985; Ritchie and Dunlap, 1980; Burdett et al., 1983; Sutton, 1983; Ritchie, 1984).

Rapid and vigorous root growth after transplanting is widely held to be one of the most critical factors affecting the ability of a seedling to obtain an adequate supply of water and nutrients immediately after planting (Larson, 1970, 1975; Farmer, 1975; Sutton, 1980; Ritchie and Dunlap, 1980; Burdett et al., 1983). For spring planted seedlings an early supply of moisture is essential to support shoot elongation and leaf expansion immediately after planting (e.g., Webb and Dumbroff, 1978). In species such as red oak for which shoot growth occurs in distinct flushes, the first flush of stem and leaf growth after outplanting may determine the success or failure of the seedling.

RGP tests were devised as a method to assess the capacity of planting stock to initiate and elongate roots when placed in an environment favorable for root growth (Stone, 1955; Ritchie, 1985). In general, RGP is measured by placing seedlings in a controlled environment (such as a greenhouse), holding them for a standard period (usually about one month), and then assessing the amount of root growth that has taken place (Ritchie, 1985). In practice, a wide variety of media for root growth have been used, including different types of potting mixes (peat, vermiculite, sand, soil and various mixtures of same, see for example Stone, 1955; Larson, 1975; van den Driessche, 1978) or hydroponic systems using different nutrient solutions (e.g. Reid et al., 1988). Different photoperiods and different temperatures of air and soil have been used in RGP tests (e.g. Larson, 1970). Methods used to assess the amount of root growth have also varied considerably, including measurement of numbers of new roots, length of new roots, volume of new roots, or weight of new roots (Ritchie and Dunlap, 1980).

A number of researchers have tried to establish correlations between RGP and other seedling characteristics (such as diameter, or other seedling "size" variables). In general, RGP has been positively correlated with seedling root collar diameter (e.g. Khajjidoni and Land, 1988; South et al., 1988) and initial root mass or volume (Carlson, 1986; Feret, 1989). Researchers have also tried to establish a relationship between RGP and survival and growth of outplanted seedlings. Outplanting survival can sometimes be correlated with RGP, but generalizations are difficult to make because of the great variety of RGP testing procedures used and variation in reporting results. Under most circumstances, however, it is unlikely that a seedling outplanted in the field could express the same degree of root development as the same seedling grown under nearly optimum conditions (Ritchie, 1985).

Sutton (1980) suggested that the ability of a seedling to augment its root system after outplanting could not be determined by a visual inspection of the seedling. However, photographs included in some of the studies mentioned above (e.g. Stone, 1955) show that in many cases new root growth occurred as an extension of a pre-existing large diameter lateral that was suberized proximal to the taproot. In fact, in a subsequent study Stone et al. (1962) reported that measurable root growth was primarily the result of elongation of previously existing laterals. If a significant proportion of new root growth does take place on the permanent first-order lateral roots that are lifted with the seedling, then a morphological assessment of the number of large lateral roots on a seedling root system should indicate the potential for root growth after the seedling is outplanted. Hence, this study was undertaken to examine the relationship between the number of large first-order laterals (suberized, and very likely to survive lifting, handling, storage and planting procedures) and root growth potential for nursery-run red oak seedlings that were representative of those used in the field trials reported in this manuscript.

Materials and Methods

The seedlings used for evaluation of RGP were a subsample of the 1-0 bare-root stock that was divided into 3 groups based on the number of large first-order lateral roots present on the seedling after lifting (see general information in Materials and Methods section of Part I). Ten seedlings of each of the three root grade groups (those with 0-4, 5-9, and 10 or more permanent first-order lateral roots) were planted in two gallon plastic pots in a potting mix of two parts "hortsoil": one part "Krumbles" perlite and placed on a greenhouse bench. Seedlings were planted 4 May 1987 and grown under an 18-hour photoperiod at ambient temperatures ranging from 18 to 30 degrees C for 26 days. Seedlings were watered daily. At the end of the 26-day period, seedlings were carefully removed from the pots and excess potting medium was gently rinsed from the roots. One seedling never broke bud and was discarded from the analysis. Measurements made on each seedling included shoot height to the nearest 0.1 cm, diameter to the nearest 0.1 mm just above the root collar, and the number of new (white) roots (classified as first-, second-, or third-order laterals). New root extensions at the tips of previously existing first-order roots were counted as new first-order lateral roots (old roots were not counted after the original root grading was completed). Roots branching from any first-order root (new or old) were counted as second-order laterals, and new roots arising from any second-order root were counted as third order laterals. Root systems of at least two representative seedlings from each root grade group were photographed. Shoots, lateral roots, and taproots were separated and dried for at least 24 hours at 65 degrees C for determination of dry weights.

Data were analyzed using Statistical Analysis System (SAS) programs (SAS Institute, 1985). Analysis of variance was done using the general linear models procedure of SAS.

Results and Discussion

Mean values for each root grade group for all parameters measured and results of analysis of variance are given in Table 1. The mean root grade (number of large first-order lateral roots) values indicate a fairly even distribution of seedlings within the root grade groups (e.g. values round to the

Table 1. Mean values of seedling characteristics for three root grade groups.

Characteristic	Mean Group 1	Mean Group 2	Mean Group 3	F	Pr>F
Root grade	1.6	6.8	11.6		
Height (cm)	33.7	46.0	47.0	2.80	.0791
Diameter (mm)	4.9	7.4	7.6	19.81	.0001
New 1st order laterals	2	6	12	3.28	.0538
New 2nd order laterals	29	96	148	3.66	.0399
New 3rd order laterals	29	147	418	4.60	.0195
Shoot dry weight (g)	1.90	5.31	5.89	17.42	.0001
Taproot dry weight (g)	1.82	4.78	5.10	22.53	.0001
Lateral root d.w. (g)	0.12	0.42	0.93	10.00	.0006
Total root dry weight (g)	1.94	5.21	6.03	26.21	.0001

median for the divisions used). Differences for seedling shoot characteristics (height and diameter) are most dramatic for group 1 (0-4 roots) versus groups 2 (5-9 roots) and 3(10 or more roots). Differences in height were not statistically significant ($p < 0.05$). Although the ANOVA indicates that diameter differences are statistically significant, the difference (0.2 mm) between group 2 and group 3 may not be biologically significant, and certainly could not be used on an operational basis to separate seedlings during grading.

Root growth potential is indicated by the numbers of new first-, second-, and third-order laterals that were counted on each seedling. Mean numbers of new lateral roots for each group clearly indicate that there is a positive relationship between root grade and root growth potential measured in this manner. ANOVA results support the hypothesis that numbers of large first-order lateral roots may be used to predict root growth potential, especially the potential for development of critical new second- and third-order roots.

Dry weights of different plant parts were included in the analysis because they provide a reasonably robust and precise measure of seedling balance (e.g., root to shoot ratios) and are positively correlated with overall seedling vigor. Significant differences in mean shoot, taproot, lateral root, and total root dry weights were present among the three root grade groups.

Figure A1 shows root system morphologies representative of the seedlings. New root extensions on relatively large suberized roots were important, and extensive branching into second- and third-order roots occurred on nearly all seedlings from groups 2 and 3 (Figure A1a). In a number of cases, new first-order roots were initiated at the lifting wound at the base of the taproot (Figure A1b).

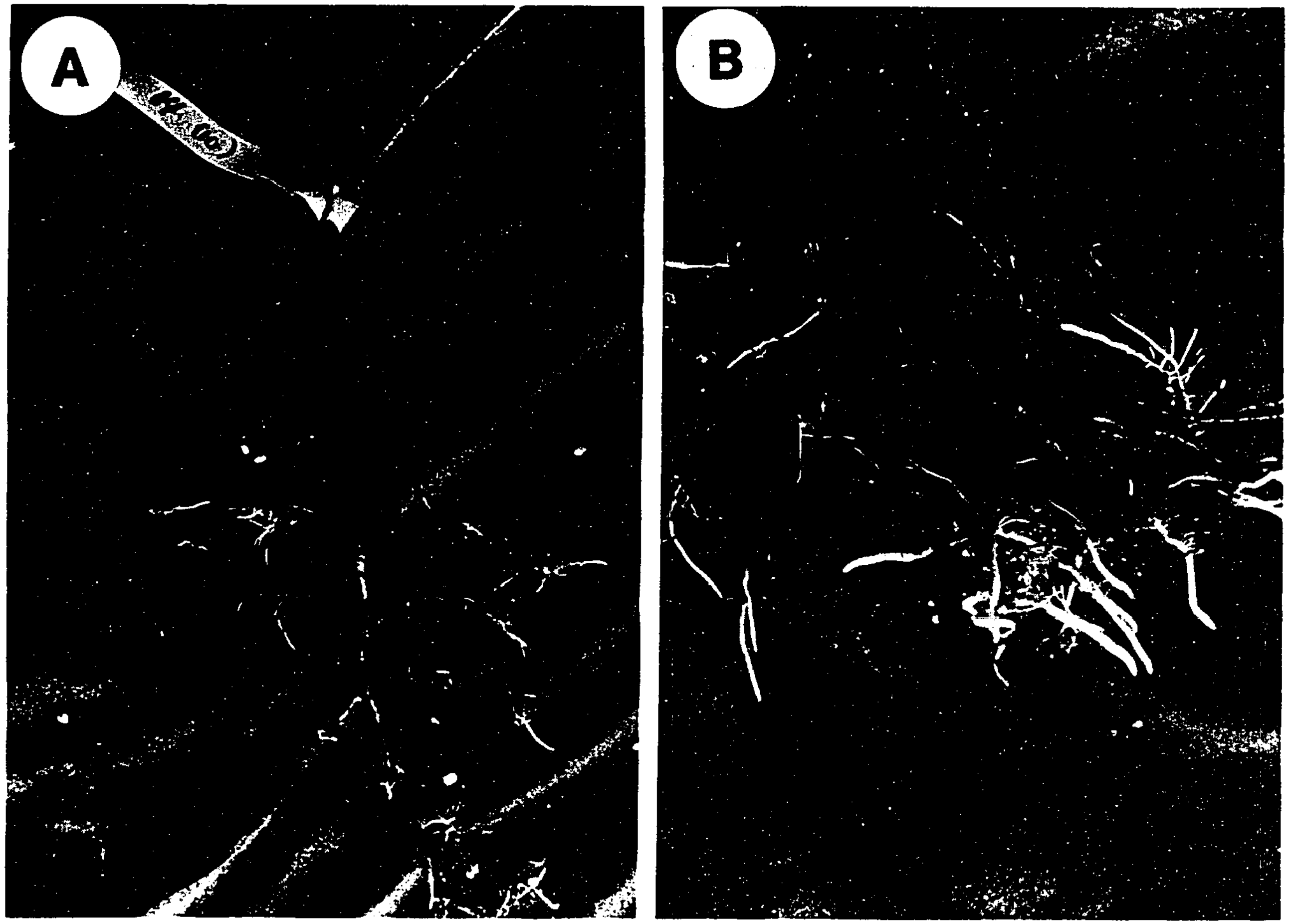
Conclusions

While seedling physiology is probably the ultimate factor determining seedling performance, time-consuming and labor-intensive physiological tests are more difficult for nursery personnel to perform than simple morphological evaluations which can be done as seedlings are prepared for shipping. The strong linear relationships between number of large first-order lateral roots and root growth potential and between first-order lateral roots and plant part dry weights indicate that visual evaluation of seedling root systems could be used to predict the potential for seedling root development and success in the field. In addition, it appears that number of first-order lateral roots may be a better indicator of seedling establishment ability (in terms of root development) than the oft-used height and diameter grading criteria.

Figure A1. Root system morphology of seedlings after root growth potential test

(A) New root tips were white, branching into second and higher order roots on many seedlings

(B) Large white roots (callus roots) occurred at cut end of taproot


A
B

Literature cited

Burdett, A. N., D. G. Simpson, and C. F. Thompson. 1983. Root development and plantation development success. Plant and Soil 71:103-110.

Carlson, W. C. 1986. Root system considerations in the quality of loblolly pine seedlings. S. Jour. Appl. For. 10:87-92.

Farmer, R. E. 1975. Dormancy and root regeneration of northern red oak. Can. J. of For. Res. 5:176-185.

Feret, P. P. 1989. Root growth and root regeneration testing on hardwoods. Pp. 74-83 in "Roots--Foundation of Quality Seedlings", Proc. Northeastern Area Nurserymen's Conference, 24-27 July 1989, Peoria, IL.

Feret, P. P., and R. E. Kreh. 1985. Seedling root growth potential as an indicator of loblolly pine field performance. For. Sci. 31:1005-1011.

Khajjidoni, S. T., and S. B. Land. 1988. Family effects on root characteristics and root growth potential of American sycamore seedlings. Pp 108-115 in Proc. Tenth No. Amer. For. Biol. Workshop, 1988, Univ. of British Columbia.

Larson, M. M. 1970. Root regeneration and early growth of red oak seedlings: influence of soil temperature. For. Sci. 16:442-446.

Larson, M. M. 1975. Pruning northern red oak nursery seedlings: effects on root regeneration and early growth. Can J. For. Res. 5:381-386.

Reid, R. K., A. E. Miller, and R. W. Rose. 1988. Carbohydrate resources and root growth potential in selected families of loblolly pine. Proc. Tenth No. Amer. For. Biol. Workshop, 1988, Univ. of British Columbia.

Ritchie, G. A. 1984. Assessing seedling quality. Pp. 243-259 in Duryea, M. L., and T. D. Landis, eds., Forest Nursery Manual: Production of Bareroot Seedlings. Nijhoff/Junk Pub. for Forest Res. Lab., Oregon State University, Corvallis, OR.

Ritchie, G. A. 1985. Root growth potential: principles, procedures, and predictive ability. Pp. 93-105 in Duryea, M. L., ed., Evaluating Seedling Quality: Principles, Procedures and Predictive Abilities of Major Tests. Oregon State University, Corvallis, OR.

Ritchie, G. A., and J. R. Dunlap. 1980. Root growth potential: its development and expression in forest tree seedlings. N. Z. J. For. Sci. 10:218-248.

SAS Institute, Inc. 1985. SAS User's Guide: Basics. Version 5 Edition. SAS Institute, Inc., Cary, North Carolina. 1290 pp.

South, D. B., H. S. Larsen, H. M. Williams, and J. N. Boyer. 1988. Use of seedling size as a covariate for root growth potential studies. Pp 89-93 in U.S.D.A. For. Serv. Gen. Tech. Rep. SO-74.

Stone, E. C. 1955. Poor survival and the physiological condition of planting stock. For. Sci. 1:90-94.

Stone, E. C., J. L. Jenkinson, and S. L. Krugman. 1962. Root-regenerating potential of Douglas-fir seedlings lifted at different times of the year. For. Sci. 8:288-297.

Sutton, R. F. 1980. Planting stock quality, root growth capacity, and field performance of 3 boreal conifers. N. Z. J. For. Sci. 10:54-71.

Sutton, R. F. 1983. Root growth capacity: relationship with field root growth and performance in outplanted jack pine and black spruce. Plant and Soil 71:111-122.

van den Driessche, R. 1978. Seasonal changes in root growth capacity and carbohydrates in red pine and white spruce nursery seedlings. In A. Riedacker and J. Gagnaire, eds., Physiologie des Racines et Symbioses, Comptes-Rendus, I.U.F.R.O., Nancy, France.

Webb, D. P., and E. B. Dumbroff. 1978. Root growth in seedlings of Acer Saccharum. In A. Reidacker and J. Gagnaire, eds., Physiologie des Racines et Symbioses, Comptes-Rendus, I.U.F.R.O., Nancy, France.

APPENDIX B. SOIL DESCRIPTIONS AND LEGAL DESCRIPTIONS FOR OUTPLANTING SITES

Site: Fick Observatory, first plot
Described by: J. Thompson, J. Kean; 10-90
Series name: Lester
Location: Boone County, Ia., west of Moingona; Sec. 12, T. 83 N., R. 27 W.
Parent material: Glacial till
Physiography: Summit position
Slope: 1-2%

A1 (0-9 cm). Dark brown (10YR 3/3) silt loam; strong medium and fine granular structure; very friable; 5% coarse fragments present; common fine and many very fine roots; few medium and many fine and very fine pores; gradual smooth boundary.
A2 (9-19 cm). Dark brown (10YR 3/3) silt loam; weak fine platy structure parting to fine and very fine granular; very friable; 6% coarse fragments present; few medium and common very fine roots; few medium and few very fine pores; gradual smooth boundary.
E (19-28 cm). Dark brown (10YR 4/3) silt loam; weak fine platy structure parting to medium and fine granular; friable; few fine distinct yellowish brown (10YR 5/6) mottles; very few thin discontinuous brown (10YR 5/3) clay films; 8% coarse fragments present; few fine and very fine roots; few medium, fine, and very fine pores; clear smooth boundary.
2Bt1 (28-38 cm). Dark yellowish brown (10YR 4/4) clay loam; moderate medium and fine subangular blocky structure; firm; common fine distinct yellowish brown (10YR 5/6) mottles; thin discontinuous dark brown (10YR 4/3) clay films; 6% coarse fragments present; few fine and very fine roots; few medium and fine pores; gradual smooth boundary.
2Bt2 (38-50 cm). Dark yellowish brown (10YR 4/6) clay loam; strong medium subangular blocky structure; firm; common medium indistinct brownish yellow (10YR 6/8) mottles; thick continuous dark yellowish brown (10YR 4/4) clay films; 6% coarse fragments present; few fine and very fine roots; few medium and fine pores; gradual smooth boundary.
2Bt3 (50-64 cm). Dark yellowish brown (10YR 4/6) clay loam; weak coarse and moderate medium subangular blocky structure; very firm; thick continuous dark brown (7.5YR 3/4) clay films; 5% coarse fragments present; very few fine roots; few medium and fine pores; gradual smooth boundary.
2Bt4 (64-80 cm). Dark yellowish brown (10YR 4/6) clay loam; weak coarse subangular blocky structure; friable; thin discontinuous dark yellowish brown (10YR 4/4) clay films; 5% coarse fragments present; few fine and very fine roots; few fine and very fine pores; gradual smooth boundary.

2Bt5 (80-95 cm). Dark yellowish brown (10YR 4/6) clay loam; weak coarse and medium subangular blocky structure; firm; common medium distinct strong brown (7.5YR 4/6) mottles; thin discontinuous brown (10YR 5/3) clay films; 5% coarse fragments present; few very fine roots; few medium and fine pores; dark brown (7.5YR 3/2) infillings; gradual smooth boundary.
BCt (95-103 cm). Yellowish brown (10YR 5/4) clay loam; massive structure; very firm; common fine distinct strong brown (7.5YR 5/6), common fine distinct yellow (10YR 7/8), and few medium distinct greenish gray (5GY 6/1) mottles; thin discontinuous dark brown (10YR 4/3) clay films; 6% coarse fragments present; few fine roots; few fine and medium pores; black (10YR 2/1) infillings in some pores.

Site: Fick Observatory, 2nd plot
Described by: J. Thompson, M. Thompson, R. Schultz; 10-26-89
Series name: Le Sueur
Location: Boone County, Ia., west of Moingona; Sec. 12, T. 83 N., R. 27 W.
Parent material: Glacial till
Physiography: Sideslope
Slope: 3%

Ap (0-20 cm). Very dark gray brown (10YR 3/2) silt loam; moderate fine platy parting to moderate fine granular structure; friable; few coarse and medium, many fine and very fine roots; many medium pores; abundant earthworm fecal material; clear smooth boundary.
A1 (20-28 cm). Very dark gray brown (10YR 3/2) silt loam; weak fine platy parting to weak fine subangular blocky structure; friable; thin discontinuous light gray (10YR 7/2, dry) silt coatings; common medium and fine roots; many medium pores; gradual smooth boundary.
A2 (28-40 cm). Very dark gray brown (10YR 3/2) silty clay loam; moderate medium and fine subangular blocky structure; firm; thin discontinuous light gray (10YR 7/2, dry) silt coatings; common fine and medium roots; many medium pores; gradual smooth boundary.
2Bt1 (40-62 cm). Very dark gray brown (10YR 3/2) and dark brown (10YR 4/3) clay loam; strong medium subangular blocky and angular blocky structure; firm; thin continuous dark gray brown (10YR 4/2) clay coatings; common fine and medium roots; common medium pores; 5% (estimated by volume) coarse fragments; clear smooth boundary.
2Bt2 (62-95 cm). Brown (10YR 5/3) and yellowish brown (10YR 5/8) clay loam; strong fine and medium prismatic structure; very firm; common thick continuous black (10YR 2/1) coatings in channels, thick continuous very dark gray (10YR 3/1) and dark grayish brown(10YR 4/2) coatings on ped faces; few fine roots; common very fine pores; 8% (estimated by volume) coarse fragments.

Site: Fick Observatory, 3rd plot
Described by: J. Thompson, M. Thompson; 10-26-89
Series name: Cordova (probably a taxadjunct due to coarse materials at depth)
Location: Boone County, Ia., west of Moingona; Sec. 12, T. 83 N., R. 27 W.
Parent material: Local colluvium, mixed loess and till
Physiography: Small closed depression
Slope: Less than 1%

A1 (0-15 cm). Black (10YR 2/1) clay loam; strong fine and very fine subangular blocky structure; very friable; many fine and very fine roots; common fine and very fine channels; common earthworm fecal pellets; clear smooth boundary.
A2 (15-23 cm). Black (10YR 2/1) loam; strong fine granular structure; very friable; many very fine roots; few fine and medium pores; gradual smooth boundary.
A3 (23-36 cm). Black (10YR 2/1) clay loam; medium parting to fine and very fine subangular blocky structure; friable; common fine and very fine roots; common medium and fine pores; clear smooth boundary.
AB (36-56 cm). Very dark gray (10YR 3/1) clay loam; strong medium parting to moderate fine subangular blocky structure; friable; few fine brown (10YR 5/3) channel fillings; common fine and very fine roots; many very fine, common fine and medium pores; gradual smooth boundary.
Bt1 (56-67 cm). Dark gray (10YR 4/1) clay loam; moderate fine prismatic parting to moderate medium subangular blocky structure; firm; thin continuous very dark gray (10YR3/1) clay films, common very dark gray (7.5YR 3/0) nodules (1-5mm diam.); few fine prominent strong brown (7.5YR 5/6) mottles; few fine and very fine roots; few coarse, medium and fine pores; clear smooth boundary.
Bt2 (67-85 cm). Grayish brown (10YR 5/2) clay loam; moderate medium prismatic parting to moderate medium subangular blocky structure; very firm; thin continuous dark gray (10YR 4/1) clay films on vertical ped faces; many fine prominent yellowish brown (10YR 5/6) mottles; common very dark gray (10YR 3/1) coatings and channel fillings; few very fine roots; few medium and fine pores; clear wavy boundary.
Bt3 (85-105 cm). Grayish brown (2.5Y 5/2) clay loam; moderate medium prismatic structure; firm; thin continuous dark gray (10YR 4/1) clay films; few fine distinct yellowish brown (10YR 5/6) mottles; common very dark grayish brown (10YR 3/2) channel fillings and sandy "pockets" (sand lens or krotovina?); few very fine roots; few very fine pores; clear smooth boundary.
C (105-127 cm). Dark grayish brown (10YR 4/2) sandy loam; massive structure; friable; common medium distinct yellowish brown (10YR 5/6) mottles; common medium and very fine channel pores; abrupt boundary to silty material below.

Site: Hinds farm
Described by: J.R. Thompson, M.L. Thompson; 11-23-88
Series name: Spillville
Location: Story County, Ia, north of Ames; Sec. 26, T.84 N., R. 24 W.
Parent material: Local alluvium
Physiography: Floodplain of Skunk River
Slope: Less than 1%

A1 (0-18 cm). Black (10YR 2/1) silt loam; strong very fine subangular blocky and very fine granular structure; very friable; many fine and very fine roots; many fine and very fine pores, few large pores; abrupt smooth boundary.
A2 (18-30 cm). Black (10YR 2/1) silt loam; moderate medium and fine subangular blocky structure parting to strong very fine subangular blocky; very friable; many fine roots; many fine pores, few large pores; gradual smooth boundary.
A3 (30-47 cm). Black (10 YR 2/1) silt loam; weak medium and fine subangular blocky structure; friable; many fine roots; many fine and few large pores; gradual smooth boundary.
A4 (47-69 cm). Black (10 YR 2/1) silty clay loam; moderate medium and fine subangular blocky structure; friable; common fine roots; common fine and very few large pores; gradual smooth boundary.
AC (69-96 cm). Black (10 YR 2/1) clay loam; weak coarse subangular blocky structure; friable; few fine roots; few fine pores; gradual smooth boundary.
C (96-110 cm). Black (10YR 2/1) clay loam; massive; friable; no effervescence.

Site: Rhodes farm, 1st plot
Described by: J. Kean, J. Thompson; 10-11-90
Map unit: Colo
Location: Marshall County, Ia., south of Rhodes; Sec. 18, T. 82 N., R. 20 W.
Parent material: Local alluvium
Physiography: Floodplain or first terrace
Slope: Less than 1%

A1 (0-18 cm). Black (10YR 2/1) silt loam; moderate fine and very fine granular structure; very friable; many fine and very fine roots; many fine and very fine and common medium pores; gradual smooth boundary.
A2 (18-27 cm). Black (10YR 2/1) silt loam; moderate fine and very fine granular structure; very friable; common medium, fine, and very fine roots; common medium, fine, and very fine pores; gradual smooth boundary.
A3 (27-44 cm). Black (10YR 2/1) silt loam; weak fine and very fine granular; very friable; few medium and common fine roots; common fine and very fine pores; gradual smooth boundary.

A4 (44-59 cm). Black (10YR 2/1) silty clay loam; weak medium subangular blocky structure parting to weak fine granular; very friable; black (10YR 2/1) coatings on ped faces; few fine and very fine roots; few medium and fine pores; gradual smooth boundary.
A5 (59-86 cm). Black (10YR 2/1) silt loam; weak fine prismatic parting to medium and fine subangular blocky structure; very friable; coatings similar to horizon above; few fine and very fine roots; few medium and fine pores; gradual smooth boundary.
AC (86-103 cm). Black (10YR 2/1) clay loam; weak fine subangular blocky structure, firm; black (7.5YR 2/0) coatings on ped faces; few fine roots; few fine pores.

Site: Rhodes farm, 2nd plot
Described by: M. Thompson, J. Thompson; 10-9-89
Map unit: Gara
Location: Marshall County, Ia., south of Rhodes; Sec. 18, T. 82 N., R. 20 W.
Parent material: Local colluvium, loess over paleosol and Pre-Illinoian till
Physiography: Near base of slope, east aspect
Slope: 26%

A1 (0-22 cm). Very dark gray (10YR 3/1) silt loam; strong medium and fine granular structure; very friable; 1% coarse fragments present; many very fine, fine and medium roots; many very fine, fine and medium pores; many pores are filled with fecal pellets; gradual wavy boundary.
A2 (22-40 cm). Dark grayish brown (10YR 4/2) silt loam; weak fine and very fine subangular blocky structure; friable; few thin discontinuous light gray (10YR 7/2) silt coatings; few thin continuous very dark gray (10YR 3/1) organic coatings and channel fillings; pockets of earthworm fecal material common; 8% coarse fragments (estimated by volume); many fine and very fine roots; many coarse, medium, and fine pores; clear smooth boundary.
Bw1 (40-50 cm). Brown (10YR 4/3) silt loam; weak fine and medium subangular blocky structure; friable; few thin discontinuous light gray (10YR 7/2) silt coatings; common very dark gray (10YR 3/1) channel fillings up to 5 mm in diameter; few medium distinct yellowish brown (10YR 5/6) mottles; 4% coarse fragments; many fine and very fine and few medium roots; many fine and very fine and few medium pores; abrupt smooth boundary ("stone line"--concentration of 1-2-cm-diameter gravel at 50 cm).
Bw2 (50-75 cm). Brown (10YR 5/3) clay loam; strong fine and medium subangular blocky structure; very friable; common fine distinct yellowish brown (10YR 5/6) mottles; 3% coarse fragments; many fine and very fine roots; many fine and very fine pores; gradual smooth boundary.

2Bt1 (75-95 cm). Strong brown (7.5YR 5/6) and grayish brown (10YR 5/2) clay; moderate medium prismatic structure parting to moderate medium and fine subangular blocky; firm; thick continuous dark grayish brown (10YR 5/2) and dark brown (7.5YR 4/4) clay films on ped faces; 2-5% coarse fragments; common fine and very fine roots; common fine and very fine pores; clear smooth boundary.
3Bt2 (95-105 cm). Strong brown (7.5YR 5/6) and grayish brown (10YR 5/2) clay (with pockets of strong brown (7.5YR 5/8) and yellowish red (5YR 5/6 sandy clay loam); moderate medium prismatic parting to moderate medium subangular blocky structure; firm; common thick continuous dark grayish brown (10YR 4/2) clay films; few thin continuous red (2.5YR 4/6) clay films on ped faces and lining channels; 2-5% coarse fragments; common very fine roots; common fine and very fine pores. (Probably Pre-Illinoian till at 95 cm.)

Site: Rhodes farm, 3rd plot
Described by: J. Kean, J. Thompson; 10-11-90
Series name: Mystic
Location: Marshall County, Ia., south of Rhodes; Sec. 18, T. 82 N., R. 20 W.
Parent material: Loess over paleosol and Pre-Illinoian till
Physiography: Mid-slope, east aspect
Slope: 26%

A1 (0-12 cm). Very dark grayish brown (10YR 3/2) and dark yellowish brown (10YR 4/6) silt loam; moderate medium granular structure; very friable; 3% coarse fragments; common medium, fine and very fine roots; common medium fine and very fine pores; gradual smooth boundary.
EB (12-23 cm). Dark yellowish brown (10YR 3/4) and yellowish brown (10YR 5/4) silt loam; weak medium platy parting to weak medium and fine granular structure; friable; 3% coarse fragments; few thin discontinuous pale brown (10YR 6/3) silt coatings; few fine yellowish brown (10YR 5/8) mottles; common fine and few very fine roots; few medium, common fine and very fine pores; clear smooth boundary.
Bt1 (23-36 cm). Dark yellowish brown (10YR 4/6) silty clay loam; weak medium and fine subangular blocky structure; friable; coarse fragments present; few thin discontinuous pale brown (10YR 6/3) silt coatings; few thin discontinuous dark brown (7.5YR 4/4) clay films; few fine yellowish brown (10YR 5/6) mottles; few fine and very fine roots; few fine and very fine pores; gradual smooth boundary.
2Bt2 (36-51 cm). Strong brown (7.5YR 4/6) and brown (7.5YR 5/4) sandy clay loam; moderate medium subangular blocky structure; firm; few thin discontinuous dark brown (7.5YR 3/4) clay films; coarse fragments present; few fine and very fine roots; few fine and very fine pores; gradual smooth boundary.

2Bt3 (51-64 cm). Strong brown (7.5YR 5/8) and yellowish brown (10YR 5/6) sandy clay loam; moderate medium subangular and angular blocky structure; firm; few very thin continuous strong brown (7.5YR 4/6) clay films; coarse fragments present; few fine and very fine roots; few fine and very fine pores; gradual smooth boundary.
2BCt (64-84 cm). Strong brown (7.5YR 5/8) sandy clay loam; strong medium subangular and angular blocky structure; very firm; thin continuous strong brown (7.5YR 4/6) clay films; common thin discontinuous brown (7.5 YR 5/4) silt coats on some ped faces; coarse fragments present; few fine and very fine roots; few fine and very fine pores.

Site: Rhodes farm, 4th plot
Described by: J. Kean, J. Thompson; 10-12-90
Map unit: Downs
Location: Marshall County, Ia., south of Rhodes; Sec. 18, T. 82 N., R. 20 W.
Parent material: Loess over till or colluvium and Pre-Illinoian paleosol
Physiography: Summit
Slope: 1-2%

A (0-10 cm). Very dark grayish brown (10YR3/2) silt loam; moderate medium and fine granular structure; very friable; common medium, fine and very fine roots; common medium, fine and very fine pores; clear smooth boundary.
AB (10-18 cm). Yellowish brown (10YR 5/6) and dark grayish brown (10YR 4/2) silt loam; moderate medium and fine granular structure; very friable; few medium and common fine and very fine roots; few medium and common fine and very fine pores; clear smooth boundary.
Bt1 (18-26 cm). Yellowish brown (10YR 5/6) silty clay loam; weak medium subangular blocky parting to moderate medium granular structure; friable; dark gray (10YR 4/1) and dark brown (7.5YR 3/4) clay coatings in pores; common fine and very fine roots; common fine and very fine pores; clear smooth boundary.
Bt2 (26-37 cm). Yellowish brown (10YR 5/6) silty clay loam; weak medium subangular blocky parting to moderate medium granular structure; friable; thin discontinuous strong brown (7.5YR 4/6) clay films; few thin discontinuous pale brown (10YR 6/3) silt coats; few gray (10YR 5/1) clay coatings in pores; few very fine roots; few fine and very fine pores; clear smooth boundary.
2Bt3 (37-46 cm). Dark brown (7.5YR 4/4) clay loam; moderate medium subangular blocky structure; firm; thick continuous dark yellowish brown (10YR 4/4) clay films; 4% coarse fragments present; common fine distinct dark yellowish brown (10YR 4/6) mottles; few fine and very fine roots; few fine and very fine pores; gradual smooth boundary.

3Bt4 (46-71 cm). Grayish brown (10YR 5/2) clay; weak medium prismatic structure; very firm; thick continuous dark yellowish brown (10YR 4/4) clay films; many fine distinct dark yellowish brown (10YR 4/6) mottles, few fine prominent yellowish red (5YR 5/8) mottles; very few very fine roots; very few very fine pores; abrupt smooth boundary.
3BCt (71-94 cm). Grayish brown (10YR 5/2) clay; massive; very firm; shiny ped faces (slickensides?); common fine distinct strong brown (7.5YR 5/8) and few fine prominent yellowish red (5YR 5/8) mottles; very few very fine roots; very few very fine pores.

APPENDIX C. CLIMATOLOGICAL DATA AND SOIL DATA SUMMARIES

Table C1. Climatological data[a] from nearest recording station for three outplanting sites in 1987, 1988, and 1989.

	Station									
Month,	Ames (Hinds)				Boone (Fick)				Colo (Rhodes)	
year	Prp[b]	DFN[c]	Temp[d]	DFN	Prp	DFN	Temp	DFN	Prp	Temp
3/87	2.78	+0.71	42.1	+8.1	3.25	+1.11	40.1	+6.5	2.68	39.8
4/87	2.08	-1.31	54.2	+4.7	2.45	-0.87	52.7	+3.5	1.85	51.4
5/87	4.03	-0.34	66.6	+5.5	3.52	-0.99	65.3	+4.3	3.82	65.1
6/87	2.30	-2.81	73.7	+3.6	2.45	-2.72	72.5	+2.5	2.03	72.5
7/87	6.89	+3.44	74.9	+1.9	5.84	+2.02	75.6	+1.2	6.04	75.4
8/87	12.20	+8.31	70.2	-1.5	13.02	+9.15	69.0	-2.9	12.16	69.2
9/87	1.75	-1.46	64.2	+0.7	0.99	-2.36	62.7	-0.6	1.26	62.5
10/87	1.29	-1.02	48.3	-4.5	1.03	-1.28	44.4	-7.9	0.65	45.4
11/87	3.15	+1.82	42.1	+5.1	3.00	+1.58	39.0	+2.3	3.23	40.8
12/87	1.93	+1.07	28.7	+4.4	2.12	+1.07	27.0	+3.1	2.07	27.7
Annual[e]	38.65	+6.96	52.3	+4.1	38.19	+5.12	50.4	+2.4	36.15	50.6

[a]Compiled from National Oceanographic and Atmospheric Association Climatological Data for Iowa, Vol. 98, 99, and 100, National Climatic Data Center, Asheville, North Carolina.

[b]Precipitation is reported in inches.

[c]DFN refers to deviation from "normal", for precipitation it is reported in inches, for temperature it is reported in degrees F.

[d]Temperature is reported in degrees F.

[e]Annual precipitation and DFN are totals for the year, annual temperature and DFN are the means for the year.

Table C1. (Continued)

Month, year	Ames (Hinds) Prp	DFN	Temp	DFN	Boone (Fick) Prp	DFN	Temp	DFN	Colo (Rhodes) Prp	Temp
1/88	0.37	-0.37	17.1	0	0.43	-0.55	13.9	-2.9	0.53	14.6
2/88	0.21	-0.74	21.7	-1.7	0.64	-0.49	16.9	-6.2	0.24	17.5
3/88	0.38	-1.69	40.3	+6.3	0.78	-1.36	38.5	+4.9	0.60	36.6
4/88	1.72	-1.68	50.5	+1.0	1.70	-1.62	48.6	-0.06	1.27	47.0
5/88	1.75	-2.62	67.5	+6.4	1.33	-3.18	65.4	+4.4	1.85	64.7
6/88	2.09	-3.02	74.6	+4.5	2.65	-2.52	75.6	+5.3	1.16	73.6
7/88	3.39	-0.06	75.7	+1.7	2.97	-0.85	75.4	+1.0	2.03	75.7
8/88	6.07	+2.18	76.4	+4.7	4.37	+0.50	76.5	+4.6	3.79	76.5
9/88	3.29	+0.08	66.1	+2.6	4.54	+1.19	64.6	+1.3	4.06	64.4
10/88	0.27	-2.04	48.1	-4.7	0.30	-2.01	46.1	-6.2	0.45	44.9
11/88	1.93	+0.60	38.8	+1.8	2.63	+1.21	37.7	+1.0	3.58	36.4
12/88	0.77	-0.09	27.0	+2.7	0.77	-0.28	25.6	+1.7	0.51	22.8
Annual	22.24	-9.45	50.3	+2.1	23.11	-9.96	48.7	+0.7	20.1	47.89
1/89	1.12	+0.38	30.5	+13.4	1.23	+0.25	28.6	+11.8	1.03	27.2
2/89	0.30	-0.65	14.6	-8.8	0.67	-0.46	13.0	-10.1	0.46	13.0
3/89	0.73	-1.34	34.9	+0.9	0.88	-1.26	33.1	-0.5	0.38	32.6
4/89	2.58	-0.82	51.2	+1.7	2.49	-0.83	49.5	+0.3	2.8	47.9
5/89	4.16	-0.21	60.9	-0.2	3.03	-1.48	58.8	-2.2	3.49	58.3
6/89	3.49	-1.62	68.5	-1.6	4.64	-0.53	67.1	-2.9	2.44	67.3
7/89	2.43	-1.02	75.0	+1.0	2.14	-1.68	74.9	+0.5	2.77	74.9
8/89	1.73	-2.16	71.2	-0.5	2.54	-1.33	71.1	-0.8	3.92	70.6
9/89	3.20	-0.01	61.4	-2.1	3.78	+0.43	61.1	-2.2	3.87	60.4
10/89	2.90	+0.59	53.8	+1.0	3.04	+0.73	51.7	-0.6	2.51	51.9
11/89	0.11	-1.22	34.3	-2.7	0.15	-1.27	33.4	-3.3	0.05	32.5
Annual[f]	22.74	-8.08	50.6	+0.2	24.59	-7.43	49.3	-0.9	23.10	48.8

[f]Based on 11 months.

Table C2. Weighted means[a] for surface (srf)[b] and subsurface (sb) soil properties[c]

	Plot							
	H1	F1	F2	F3	R1	R2	R3	R4
Dep. A[d]	69	19	40	56	86	40	12	18
Srf. C	1.9	1.4	1.3	2.1	1.7	1.8	1.3	2.1
Sb. C	1.1	0.4	0.4	0.2	1.1	0.5	0.4	0.4
Srf. N	0.14	0.13	0.12	0.14	0.13	0.15	0.10	0.2
Sb. N	.07	.06	.05	.02	.05	.04	.04	.04
Srf. pH	7.3	5.2	5.7	6.3	5.4	5.5	5.1	5.7
Sb. pH	7.2	5.6	6.1	7.2	5.4	4.7	5.0	5.2
Srf. P	12.9	20.9	5.5	2.9	7.2	2.1	2.0	2.6
Sb. P	10.0	7.6	5.0	1.6	24.0	0.6	1.2	1.1
Srf. K	84	140	88	137	109	44	59	113
Sb. K	71	95	151	130	180	67	100	124
Srf. BD	1.25	1.40	1.41	1.43	1.54	1.32	1.28	1.20
Sb. BD	1.30	1.64	1.69	1.72	1.77	1.68	1.56	1.40
Srf. SA	32	52	33	33	52	52	57	62
Sb. SA	54	51	39	58	53	46	52	33
Srf. SI	42	34	47	40	26	34	30	19
Sb. SI	29	26	31	23	6	27	24	24
Srf. CL	25	14	20	27	22	14	13	19
Sb. CL	17	24	30	19	41	27	24	43

[a]Weighted means were calculated by multiplying the thickness of a sampled horizon by the measured value for a soil property, adding all A (or B) horizon values so calculated, and dividing by the total depth of A (or B) horizon.

[b]Surface refers to A horizon properties, subsurface refers to B horizon properties.

[c]Results for total C and N are reported as %, P and K are reported as ppm, bulk density (BD) is reported as $g*cm^{-3}$, and sand (SA), silt (SI), and clay (CL) are reported as %.

[d]Thickness of A horizon materials.